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Thermal transient analysis of high power LED tested on Al_2O_3 thin film coated Al substrate

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***Abstract* – *Aluminium Oxide (Al_2O_3) thin film was prepared on Al substrates by RF sputtering and used as heat sink material for high power Light Emitting Diode (LED). The thermal transient analysis was performed for the given LED and evaluated the parameters such as total thermal resistance, rise in junction temperature and the thermal resistance of interface material (Al_2O_3). The R_{th-tot} value of LED was low for 500 nm Al_2O_3 thin film boundary condition tested at 150 mA driving current and observed the difference in R_{th-tot} (ΔR_{th-tot}) was high (3.1 K/W) when compared to bare Al boundary condition. Improved reduction in T_J of LED ($\Delta T_J = 2.4°C$ compared with 400 nm Al_2O_3 boundary condition and $\Delta T_J = 1.9°C$ compared with bare Al) was achieved with 500 nm boundary condition measured at 350 mA. The surface morphology of Al_2O_3 thin film was also evidenced for the observation from cooling transient curve as smooth with more no. of contact points.*

Keywords — *LED, Al_2O_3, thin film, thermal transient analysis and surface properties.*

I. Introduction

Today's electronics are smaller and more powerful than ever, leading to ever increasing thermal challenges for the systems designer. Better thermal management allows more forward current to be applied to the LED, which means more light and possibly reducing the number of LEDs required for the desired light output [1]. The LED's color, or wavelength, will change with temperature. As the die temperature increases, the wavelength of the color increases. This is particularly important with white light. Thermal Interface Materials (TIMs) are designed to fill in air gaps and microscopic irregularities, resulting in dramatically lower thermal resistance and thus better cooling. The continual increase in cooling demand for solid state lighting has led to an increased focus on improving thermal interface materials. Significant advances have been made in the development of thermal greases/gels, phase-change materials (PCMs), solders, and carbon nanotubes (CNTs) as interface materials. Greases, gels, and PCMs are the most widely used, and their thermal performance has reached 10 mm^2 K/W [2].

Among the available TIM, thermal paste or greases are the ease to apply for all type of electronic devices and it is necessary to increase the thermal conductivity by adding high conductive material without affecting the physical nature. Among the fillers, Al_2O_3 is one of the most commonly used filler in polymer for TIM application since it is widely available in market and has a good thermal conductivity. Al_2O_3 has been used as a filler to change thermal and dielectric properties as well as improvement of mechanical strength [3-5]. The same author group has already reported the performance of LED using metal oxide as filler mixed with commercial thermal paste and achieved noticeable results [6]. The total thermal resistance of an interface material is composed of the bulk resistance and the contact resistances. Accordingly, the thermal resistance of an interface material can be written as follows:

$$R = R_c + BLT/k_{TIM} \qquad (1)$$

where R_c is the contact resistance, BLT is the bond-line thickness of the interface material, and k_{TIM} is the bulk thermal conductivity of that material. A high thermal conductivity can reduce the bulk thermal resistance of the interface material, but the contact resistance must also be minimized [7,8,2].

Since the BLT is a deciding factor for the best thermal heat transfer from LED package to heat sink, thin film interface material is an attracting and effective way to conduct the excess heat from the LED package to heat sink. Our group has already prepared nitrides (AlN and BN) and oxides (ZnO) thin films and used as thermal interface materials for high power LED [6, 9].

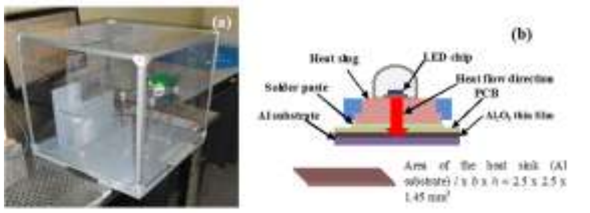

Fig. 1(a) Still air box and Fig. 1(b) Schematic diagram of LED testing configuration using Al2O3 coated Al substrate as a heat sink.

Since, Al_2O_3 thin films have a thermal conductivity of 1 W/mK for thickness of 140nm, it will allow a better thermal path for high power LED to dissipate heat. Consequently, Al_2O_3 thin film is prepared at various thicknesses on Al substrate and used as TIM. The performance of the LED was tested by attaching the Al_2O_3 thin film coated substrates as substrate at various driving currents. The observed thermal and surface properties of Al_2O_3 thin film are discussed here.

II. EXPERIMENTAL TECHNOLOGY

A. *Al_2O_3 thin film synthesis and properties*

Mg doped Al_2O_3 thin films were deposited on Al substrates (23cm x 25 cm) using Al_2O_3 (99.99% purity) target (3 inch in diameter and 4 mm in thickness) in presence of high pure Ar (99.999%) by RF sputtering (Edwards make, Model-Auto 500). The substrates were cleaned by rinsing in ultrasonic bath contains acetone and isopropyl alcohol. The base pressure of the chamber was fixed at 2.6 x 10^{-6} mbar for Al_2O_3 coatings. Two different thicknesses of (400 and 500 nm) Al_2O_3 thin films were coated at room temperature and used for this study. The thickness is measured by digital thickness monitor during the Al_2O_3 film deposition. The deposition rate and sputtering power were kept at constant as 0.4 Å / sec and 200 W, respectively. In order to remove the surface oxidation of the target, pre-sputtering was carried out for 5 min at Ar pressure of 3.5 x 10^{-3}. To achieve uniform coating, rotary drive system enabled substrate holder was used and fixed at 25 RPM for all Al_2O_3 film coatings. During coating, chamber pressure of 7.94 x 10^{-3} was maintained for all Al_2O_3 thin films with substrate to target distance of 7 cm. Few samples of Al_2O_3 thin films were annealed at 300 °C for 1 hr and used to study the influence of annealing on conducting behaviour of the film and also on thermal resistance as well as junction temperature of the given LED. The surface roughness parameters of bare and Al_2O_3 thin film coated Al substrates are measured by atomic force spectroscopy (model: ULTRA Objective, Surface Imaging Systems, GmbH) in the non-contact mode.

The morphological images were captured by using HITACHI make Scanning Electron Microscope (SEM) (Model S-3400N). The surface topography and the elemental analysis of bare and Al_2O_3 thin film coated Al substrate before and after annealing were also studied from the SEM images. In order to test the performance of thin film as TIM, the thermal transient analysis is carried out for 3W X Lamp (cool white single chip) using Al_2O_3 thin film coated Al substrate as heat sink. The thermal transient curve of the given LED measured based on the electrical test method as per JEDEC JESD-51 standards at different boundary conditions is analyzed (see Fig.1a). The thermal transient cooling curve of the LED is captured by the Thermal Transient Tester (T3Ster) in still air box.

B. *Thermal transient measurement*

During the thermal test, the LED was driven at three different currents 150 mA, 250mA and 350 mA in a still-air chamber at room temperature of 25˚C ± 1 ˚C. The LED was forward biased until 900s. Once it reaches steady state, the LED was switched off and the transient cooling curve of heat flow from the LED package was captured for another 900s. The obtained cooling profile of device under test was processed for structure functions using Trister Master Software. The schematic diagram in fig.1b shows the arrangement of Al_2O_3 thin film as TIM for high power LED.

III. RESULTS AND DISCUSSION

A. *Thermal Transient Analysis*

The thermal transient cooling curve of given LED was recorded for various boundary conditions at different driving currents and processed for thermal resistance analysis using Trister Master Software.

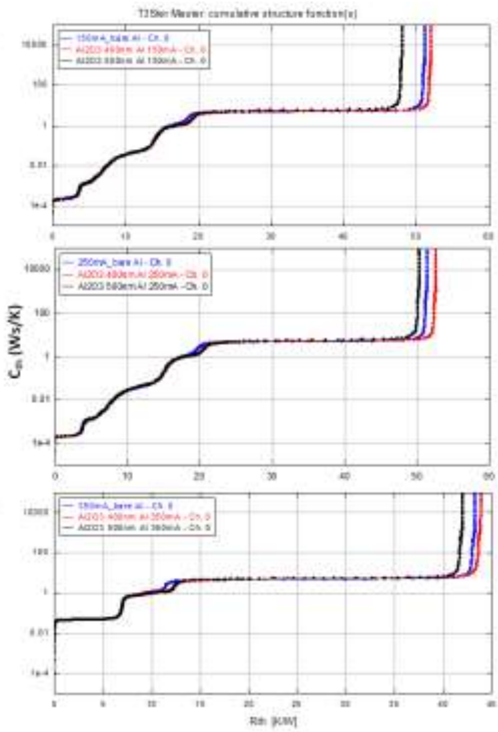

Fig. 2(a). Cumulative structure function of LED fixed on bare and Al2O3 thin film coated Al substrates

The cumulative structure function was derived from the analysis software as shown in fig.2 (a&b). From fig.2a, it explain the cumulative structure function curve of LED tested on non-annealed Al_2O_3/Al and it is visible that 500 nm Al_2O_3 samples shows low thermal resistance (R_{th}) than other samples. Moreover, fig.2a also explains the influence of driving current on R_{th} of the given LED as it increases with driving current increases. Fig.2b explain the R_{th} for the given LED fixed on annealed Al_2O_3/Al and shows high R_{th} value when compared to LED fixed on both bare Al substrates and non-annealed Al_2O_3 thin film boundary conditions. It is attributed to the crystallographic structural modification as a result of annealing [10].

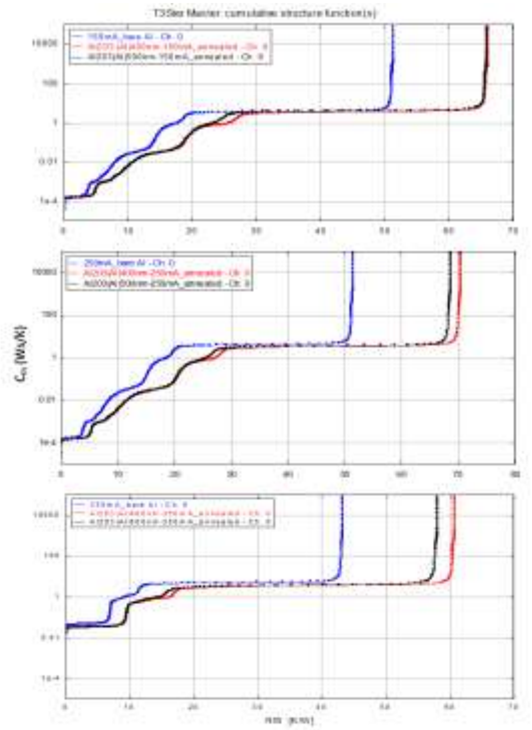

Fig. 2(b). Cumulative structure function of LED fixed on bare and
annealed (300°C) Al2O3 thin film coated Al substrates

As we know, the lower R_{th} is possible with higher driving currents and we are also observed the same for these Al_2O_3 boundary conditions. From the fig. 2a, it is clearly seen that the 500 nm Al_2O_3 thin film coated Al substrates help to reduce the R_{th} values considerably at low driving currents. It could also be observed from the fig.2a that the divergence in the cumulative structure function curve represents the conduction behaviour of interface at various driving currents. Fig 2a shows that the divergence is observed with air interface i.e. bare Al for all driving currents.

In order to understand in detail, the $R_{th\text{-}tot}$ values are evaluated from the structural function analysis curve and presented in table – 1. It clearly depicts that the low $R_{th\text{-}tot}$ is observed with 500 nm Al_2O_3 thin film boundary condition measured at 350 mA (41.8 K/W). Overall, low value in $R_{th\text{-}tot}$ is observed for 500 nm for all driving currents. When comparing 400 nm Al_2O_3 thin film boundary conditions, the difference in $R_{th\text{-}tot}$ ($\Delta R_{th\text{-}tot}$) is observed as high (4.1 K/W) and low (1.8 K/W) for 500 nm boundary condition measured at 150 mA and 350 mA respectively. As compared with bare Al and 500 nm Al_2O_3 boundary condition, noticeable reduction in $R_{th\text{-}tot}$ could be observed ($\Delta R_{th\text{-}tot}$ = 3.1 K/W) for the LED measured at 150 mA. The difference in $R_{th\text{-}tot}$ decreases as the driving current increases from 150 to 350 mA. In order to know the influence of annealing effect of Al_2O_3 thin film on thermal resistance, the LED was also tested for annealed samples (Al_2O_3 on Al) and the observed $R_{th\text{-}tot}$ value from cumulative structure function is given in same table -1.

TABLE I

PERFORMANCE OF HIGH POWER LED FOR VARIOUS BOUNDARY CONDITIONS TESTED AT THREE DIFFERENT DRIVING CURRENTS.

	Non annealed			Annealed	
Driving current (mA)	LED/Al	LED/ 400AO*/Al	LED/500AO* /Al	LED/ 400AO*/Al	LED/500AO* /Al
Total thermal resistance (K/W)					
150	50.3	51.3	47.2	65.2	64.6
250	51.5	52.6	49.5	70.4	68.6
350	43.3	43.9	41.8	60.7	58.0
Rise in Junction Temperature (°C)					
150	23.0	23.5	21.8	30.0	29.8
250	40.3	40.5	38.9	55.2	54.0
350	48.2	48.7	46.3	67.8	64.8
Thermal resistance between MCPCB and film coated substrates (K/W)					
150	31.1	32.0	27.4	37.6	38.9
250	30.3	30.6	28.1	41.8	40.4
350	30.5	29.9	28.2	42.3	40.1

It shows that the annealing effect also influence the heat flow as a result of structural changes and hence huge difference in $R_{th\text{-}tot}$ is observed with annealed Al_2O_3 thin film boundary condition irrespective to the thickness. There are few reasons for this observation for annealed Al_2O_3; i) There may be thermal mismatch between the thermal conductivity of Al_2O_3 and Al, ii) lattice mismatch between Al_2O_3thin film and Al substrate. The thermal conductivity of Al_2O_3 is very low (~ 2 W/mK) than that of Aluminium. Moreover, the lattice parameter of Al_2O_3 is large (a = 4.78 Å and c = 12.99 Å) than that of Al (a=4.05 Å) [11].

In addition to this, the thermal conductivity of Al_2O_3 diminishes as the temperature increases and this is the reason behind for the increased thermal resistance of Al_2O_3 thin film at high annealing temperatures [12,13]. During annealing, there may be possible for increased crystal defects that also affect the thermal conductivity. Hence, the increased thermal resistance is possible with annealed samples. This may lead to high thermal resistance between the two materials when it applied as an interface.

Though the BLT of 400nm Al_2O_3 samples is low, Al_2O_3 thin film restricts the heat flow from hot junction (LED) to cold end (Ambient). Crystallinity is an important parameter for thermal conductivity of the desired materials and also changes with respect to thickness. Normally, the crystalline behavior of Al_2O_3 is comparatively poor at low thickness and hence it restricts heat from one end to other end. Consequently, 500 nm thick Al_2O_3 conducts more heat than that of 400 nm thick Al_2O_3 and hence achieved low $R_{th\text{-}tot}$ value with 500 nm samples. In addition to that, there are some reasons for this variation of thermal resistance for annealed samples. Generally a thin material conducts more heat than the thick material since it has short path to conduct the heat. But it will not work for highly conductive materials even though the material has high thickness. The low $R_{th\text{-}tot}$ value for 500 nm Al_2O_3 is because of electronic conduction as the temperature increases.

In addition to $R_{th\text{-}tot}$ observation of the LED, the T_J value of the given LED was measured from the transient cooling curve and the observed values are also given in Table -1. Since the thermal conductivity behavior of the interface material decides the junction temperature of the LED, the results of T_J are co-related to $R_{th\text{-}tot}$. As consequence, reduced T_J value was achieved with Al_2O_3 boundary condition than bare Al boundary condition (air interface). The difference of rise in T_J was measured and observed as high (ΔT_J = 2.4°C) with 500 nm sample when compared with 400 nm boundary conditions while low value (ΔT_J = 2.4°C) was noticed with 500 nm boundary condition when compared with bare Al boundary condition. As we observed and described in the thermal resistance analysis, the T_J value of LED tested at annealed Al_2O_3 thin film boundary conditions was also observed as high and the results are summarized in Table – 1. It is clearly seen that a noticeable reduction in T_J value for 500 nm annealed Al_2O_3 boundary conditions is recorded when compared to 400 nm but annealed Al_2O_3 boundary conditions do not work for reduction in T_J of the given LED.

Apart from this study, a detailed analysis is necessary to understand the behavior of Al_2O_3 for interface application in electronic packaging. Consequently, the interface (Al_2O_3 thin film) resistance is evaluated from the cumulative structure function analysis (from fig. 2a & b) and summarized in Table - 1. It clearly indicates that low interface resistance is achieved with 500 nm Al_2O_3 thin film than other boundary conditions. The observed results from interface analysis are agreed with the observation made from the thermal resistance as well as junction temperature analysis.

B. Surface analysis

The surface morphology of Al_2O_3 thin film was recorded by using AFM and FESEM as shown in fig.3 and fig.4. From fig. 3, it clearly shows the influence of annealing on surface morphology of 400 nm Al_2O_3 thin film. To evidence this observation, the SEM images are also presented in same fig. 3 (b and d) and revealed the surface modification as a result of annealing. The surface roughness is a prime factor affecting the thermal conductance in thermal management. The surface roughness of Al_2O_3 thin film coated on Al substrate were measured from the AFM images and given in Table – 2.

TABLE III

SURFACE ROUGHNESS AND PARTICLE SIZE ANALYSIS OF AL2O3 THIN FILM DEPOSITED ON AL SUBSTRATES

	Roughness (nm)		Particle Size (µm)	
Al_2O_3 Thin film thickness	Non-Annealed	Annealed	Non-Annealed	Annealed
400 nm	8.9	6.7	0.6	0.37
500 nm	9.2	57	0.47	5.96

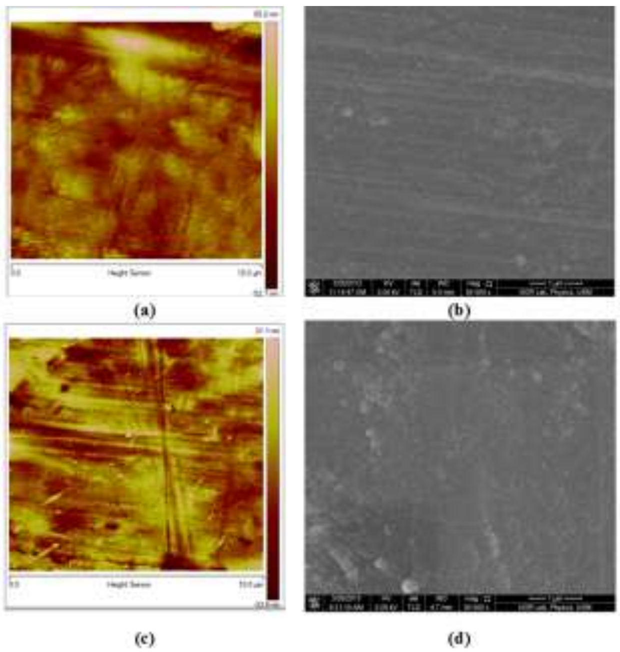

Fig. 3. Surface morphology of as grown (a&b) and 300 °C annealed (c&d) Al2O3 (400nm) thin film on Al substrate

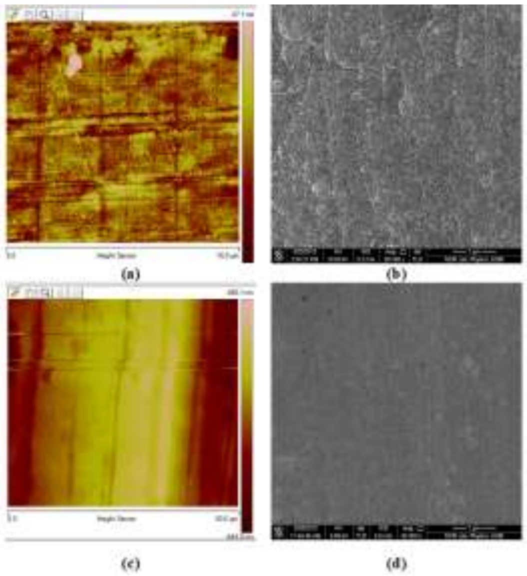

Fig. 4. Surface morphology of as grown (a&b) and 300 °C annealed (c&d) Al2O3 (500nm) thin film on Al substrate

It evidences the smooth surface of Al_2O_3 thin film and a small reduction in roughness could be observed for annealed sample. From fig.4, the surface modified profile was observed for 500 nm Al_2O_3 thin film and it can be clearly understood that the increase in thickness also influences the surface morphology.

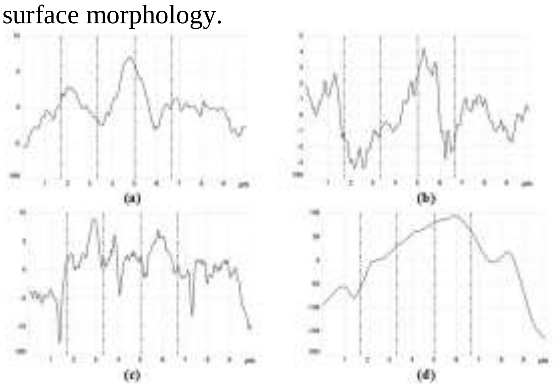

Fig. 5. Step profiles of Un annealed and annealed Al2O3 thin film of 400 nm (a&b) and 500 nm (c&d) thicknesses

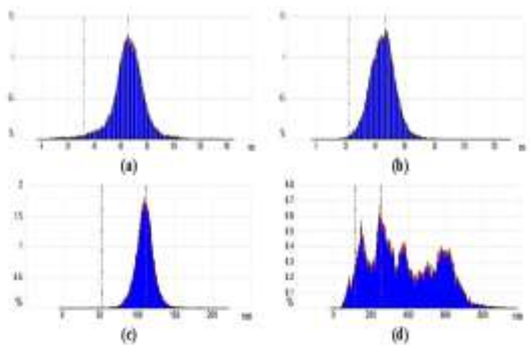

Fig. 6. Distribution of peak and valley depth on the surface of Un annealed and annealed Al2O3 thin film of 400 nm (a&b) and 500 nm (c&d) thicknesses

A small increase in surface roughness was observed for 500 nm Al_2O_3 samples and a drastic change can be observed at annealed conditions. It is clearly evidenced by recording SEM images and displayed in fig. 4 (b&d).

The thermal conductance is related to no. of points made contact with the surface of the material. So it is necessary to study the surface step profile for the Al_2O_3 thin film. Consequently, the recorded AFM images for Al_2O_3 thin film was processed by AFM software and recorded the step profile for all samples as shown in fig.5. It clearly indicates that the 500 nm Al_2O_3 thin film shows large no. of contacts than other thin film samples and hence increased thermal conductance was noticed with this boundary condition. In addition, a peak and valley depth analysis is also considered and observed profiles are shown in fig. 6. It gives the distribution of peak and valley depth on the surface of non-annealed and annealed Al_2O_3 thin film samples. It reveals that the 500 nm Al_2O_3 thin film samples show the large distribution percentage in the range of 75 to 150 nm of distance of peak – valley depth. This will create more no. of contacts and hence the high thermal conductance too. As we know, if there are large no. of contact points which also results the increased contact resistance. So large total thermal resistance as well as $R_{th\text{-}b\text{-}hs}$ was achieved for all boundary condition than 500 nm Al_2O_3 thin film (non-annealed). The particle size of all thin films is also observed from the AFM analysis and given in same table – 2. it also shows that the particle size (0.47µm) of 500 nm Al_2O_3 thin film samples is lying between the value of non-annealed and annealed 400 nm thin film sample.

IV. Conclusion

Al_2O_3 thin film was deposited on Al substrate and used as a thermal interface material for high power LED. The thermal performance of Al_2O_3 thin film was tested by using thermal transient analysis and was good for 500 nm thick measured at lower driving current. The total thermal resistance of the LED was low when Al_2O_3 thin film coated Al substrates used as heat sink especially with 500 nm thickness. Noticeable reduction in junction temperature was achieved with 500 nm thick Al_2O_3 thin film boundary condition. Overall, based on the observed results, it is suggested to use Al_2O_3 thin film with high thickness as TIM for high power solid state lighting applications.

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