Performance of LED Using Al_2O_3 Thin Film as Thermal Interface Material

Subramani Shanmugan* and Devarjan Mutharasu

Abstract— Miniaturization of solid state lighting devices creates issues on proper heat dissipation to maintain the junction temperature within the specified range for long term application. Heat dissipation can be improved by applying a thermally conductive interface material (TIM) between light emitting diode (LED) and heat sink. Al_2O_3 is one of the oxide filler material used to increase the thermal conductivity of thermal paste. Thickness control of TIM plays a vital role and restricts the use of various materials. Based on this facts, Al_2O_3 thin film at two different thicknesses were prepared by rf sputtering on Cu substrates which was used as heat sink for high power LED. The thermal transient analysis was performed for the given LED attached with Al_2O_3 coated Cu substrates and measured low total thermal resistance (R_{th}) value at 400 nm for 350 mA. The raise in junction temperature (T_J) was also low for 400 nm boundary condition at 350 mA. To strengthen this observation, surface topography of Al_2O_3 thin film was measured and it is noticed that very low surface roughness for 400 and 500 nm Al_2O_3 thin films. The grain size measured by software analysis has supported the observation due to changes in both R_{th} and T_J with respect to driving currents. Overall, the Al_2O_3 thin film coated Cu substrates conducts less heat for high power LEDs.

Index Terms—Al_2O_3, LED, surface contact, thermal interface material, thermal resistance, thermal transient curve, thin film

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1 INTRODUCTION

Light Emitting Diode is the next generation lighting solution that will eventually replace the current lighting system. LED have a lot of advantages such as long lifetime, energy saving and environment friendly as compares to fluorescence and bulb. Although the efficiency of a high-power LED is around six times better than a standard incandescent light bulb, a significant amount of the electrical energy flowing through the device is still converted into heat. The waste heat from an LED must be conducted away to maintain the junction temperature and expected life time.

Thermal management in high power LED is a very important expects to improve the lifetime, performance and efficiency of LED. An LED rated at 50000 hours with a junction temperature of 25°C will survive only half as long with a junction temperature of 125°C.To enhance the heat flow from the hot junction of the LED to atmosphere, interface material will be used between MCPCB and heat sink to avoid the interfacial thermal resistance. Thermal paste is one among the thermal interface material (TIM) and having very low thermal conductivity. It is necessary to increase the thermal conductivity by adding high conductive material without affecting the physical nature for TIM. 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 [1-3]. 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 [4].

Zhou *et. al.*, [5] used nano sized Al_2O_3 filler and reported higher thermal conductivity. Patel *et.al.*, [6] have reported the use of Al_2O_3 as a filler to modify volume resistivity. 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. Among the ceramics employed as electronic substrates and packages, the dominant material is alumina (aluminum oxide, Al_2O_3) which is having high resistivity, good mechanical and dielectric strength, excellent thermal and corrosion stability, and the ability to provide hermetic seals (Encyclopedia Britannica, 2014). But no results have been reported so far on the use of Al_2O_3 thin film as thermal interface material. We have already prepared AlN, BN and ZnO thin film and used as thermal interface materials and achieved good results in contact conductance [7-9]. In this research, Al_2O_3 is prepared as thin films at various thicknesses on Cu substrate and used for heat sink purposes. The performance of the LED was tested by attaching the Al_2O_3 thin film coated substrates at various driving current. The observed thermal and surface properties are discussed here.

2 EXPERIMENTAL METHOD

2.1 Al_2O_3 thin film synthesis and properties

Al_2O_3 thin films were deposited on Cu substrates (23cm x 25 cm) using Al_2O_3 (99.99% purity) target (3 inch in diameter and 4 mm in thickness) by RF sputtering (Edwards make, Model-Auto 500). The base pressure of the chamber was fixed at 2.6 x 10^{-6} mbar for all coatings. High pure Ar (99.999%) was used for Al_2O_3 coatings. The substrates were cleaned by rinsing in ultrasonic bath of acetone and isopropyl alcohol. Two different thicknesses of (400 and 500 nm) Al_2O_3 thin films were coated at room temperature and the thickness is measured by digital thickness monitor. The deposition rate and sputtering power were kept constant at 0.4 Å / sec and 200 W, respectively. Pre-sputtering was carried out for 5 min at Ar pressure of 3.5 x 10^{-3} to remove the surface oxidation of the target. Rotary drive sys-

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tem enabled substrate holder was used and 25 RPM was fixed for all Al_2O_3 film coatings. All Al_2O_3 thin films were coated at chamber pressure of 7.94 x 10^{-3} 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 thermal resistance as well as junction temperature of the given LED.

The surface roughness properties of bare and Al_2O_3 thin film coated Cu substrates are measured by using atomic force spectroscopy (model: ULTRA Objective, Surface Imaging Systems, GmbH) in the non-contact mode. The morphological nature and the elemental analysis of bare and Al_2O_3 thin film coated Cu substrate before and after annealing are studied by using HITACHI make Scanning Electron Microscope (SEM) (Model S-3400N). In order to test the performance of thin film as TIM, Al_2O_3 thin film coated Cu is used as heat sink for (3W X Lamp, cool white single chip). The thermal transient characterization of the given LED for different boundary conditions is measured based on the electrical test method as per JEDEC JESD-51 standards. The thermal transient curve of the LED is captured by the Thermal Transient Tester (T3Ster) in still air box.

2.2 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.

3 RESULTS AND DISCUSSION

3.1 Thermal Transient Analysis

The transient cooling curve of LED fixed on Al_2O_3 thin film coated Cu substrates was processed and hence derived the cumulative structure function as shown in fig.1. It clearly indicates that the structure function of the LED attached on annealed Al_2O_3 thin film coated Cu substrates shows different profile than for non annealed one. Moreover, the cumulative structure function depicts that the annealed Al_2O_3 thin film restricts more heat flow than for the non annealed one. This indicates that the structure function curve shifts towards right side and shows large R_{th} value. From fig.1, the red square and green circle represent the change the surface contact resistance with respect to Al_2O_3 thickness for non annealed condition and annealed condition respectively. In addition to that, the R_{th} value increases for annealed sample noticeably as the driving current increases. The distinguish curves indicates the annealing effect of Al_2O_3 on total thermal resistance of the given LED as well as Al_2O_3 thin film. From the curves, the R_{th} values for all boundary conditions were derived and are summarized in Table - 1.

It shows that the 400 nm Al_2O_3 thin film coated Cu substrates helps to reduce the R_{th} value slightly at 350 mA when compared to bare Cu substrates. Moreover, the ΔR_{th} observed between 400 and 500 nm Al_2O_3 thin film coated substrates was high for the LED measured at 250 mA (ΔR_{th} = 2.92). It describes the influence of thickness on R_{th} for the given LED. It is attributed to the influence of bond line thickness on R_{th} as it increases with large thickness. The similar behavior on R_{th} could be observed for ZnO thin film in another work [10].

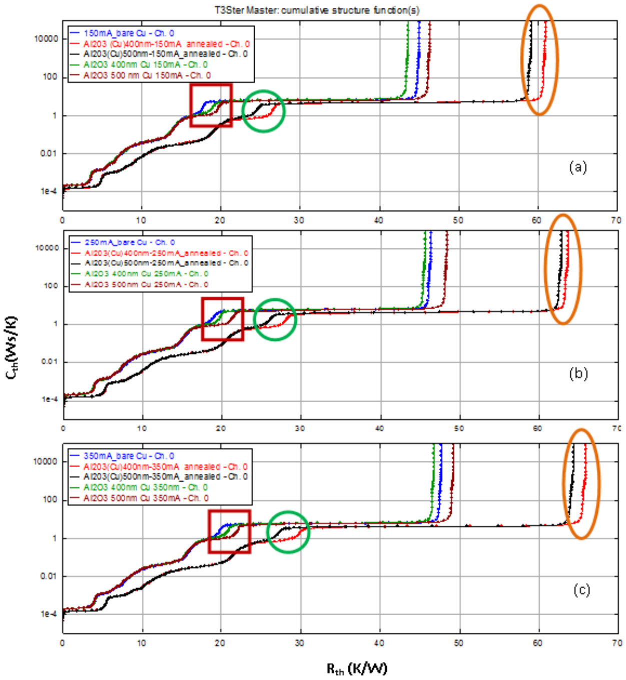

Fig.1. Cumulative Structure Function of 3W cool whight LED measured at various boundary condtions for different driving currents (a) 150 mA driving current, (b) 250 mA driving current and (c) 350 mA driving current.

In order to test the thermal effect (post processing) on material performance, the annealed Al_2O_3 thin film was also used as thermal interface material and tested for the performance of LED. The R_{th} values for annealed boundary condition were observed from the cumulative function and the values are given in the same Table – 1.

It indicates that the annealing process for the thin film will never support on reducing R_{th} and indirectly states that the increase in T_J will diminish the flow of heat from MCPCB to atmosphere while Al_2O_3 thin film used as TIM. This observation is agreed with the observed results for AlN/Al thin film

TABLE 1

VARIATION IN TOTAL THERMAL RESISTANCE AND RISE IN JUNCTION TEMPERATURE OF LED AT VARIOUS BOUNDARY CONDITIONS USING AL_2O_3 AS TIM

	Non annealed			Annealed	
Driving current (mA)	LED/Cu	LED/ 400AO*/Cu	LED/500AO* /Cu	LED/ 400AO*/Cu	LED/500AO* /Cu
Total thermal resistance (K/W)					
150	45.05	46.31	43.72	60.91	59.24
250	46.34	45.47	48.39	63.66	62.82
350	47.72	46.72	49.23	65.83	64.33
Rise in Junction Temperature (°C)					
150	20.56	20.07	21.36	28.03	27.21
250	36.18	35.78	37.96	50.20	49.38
350	52.97	52.24	54.97	73.65	72.02

*400AO – 400 nm Al_2O_3 & 500AO - 500 nm Al_2O_3

stack for TIM application [11]. It is also noticed that a small decrease in R_{th} is observed for higher Al_2O_3 film thickness ie. 500 nm.

The transient cooling curves are processed using T3Ster master software and the T_J of the given LED for each boundary condition are measured. The observed T_J values are also summarized in Table – 1. It clearly indicates that the T_J follow the same trend as observed for R_{th}. High value in ΔT_J is observed for LED fixed on 400 nm Al_2O_3 thin film coated on Cu substrates measured at 350 mA when compared with bare Cu boundary condition.

3.2 Thermal Transient Analysis

The fig. 2 shows the surface images of Al_2O_3 thin film coated on the Cu substrates before and after annealing. The first column shown in Fig. 2 shows the AFM images of 500 nm Al_2O_3 thin film before (a) and after annealing (c) respectively and the second column shown in Fig. 2 shows the SEM images of 500 nm Al_2O_3 thin film before (b) and after (d) annealing respectively. In Fig. 2, the behavior of Al_2O_3 on annealing is showed and a noticeable change could be observed for annealed samples. The SEM images clearly indicate the surface topography of prepared Al_2O_3 thin film and proved that the annealing process will provide porous structure on the surface. For thermal conductivity, the porous surface structure will not support since it has more air gaps. Hence, the thermal resistivity at the surface of porous Al_2O_3 will be more and that restricts the heat flow from the hot surface to substrate. This is the evidence from the high total thermal resistance and high junction temperature that is observed for the LED measured at various driving currents.

Fig. 3 shows the topography images of 400 nm thick Al_2O_3 thin film and the left and right columns show the images observed from AFM and SEM respectively. The first and second rows in fig. 3 show the surface images of non-annealed and annealed Al_2O_3 thin film on Cu substrates respectively. Fig.3 shows that the non annealed samples have uniform surface morphology (first row) than annealed samples. Due to annealing process, there may be a chance to have non uniform at the surface level of Al_2O_3 thin film.

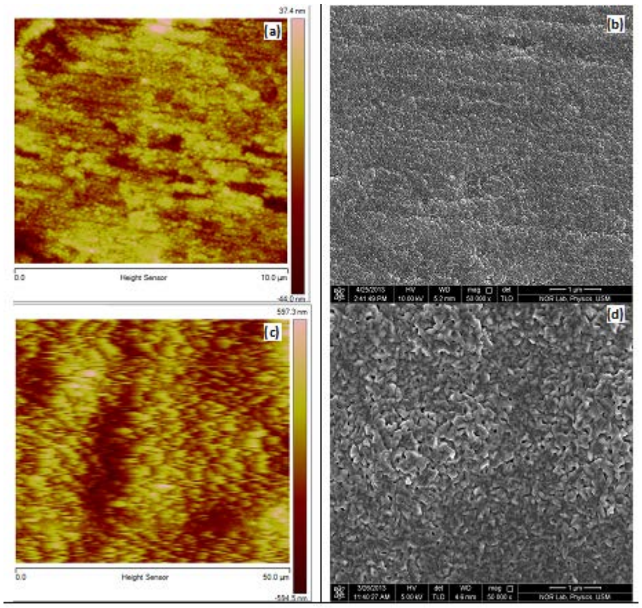

Fig. 2. Surface morphology of 500 nm Al_2O_3 thin film (a & b) before annealing and (c & d) after annealing

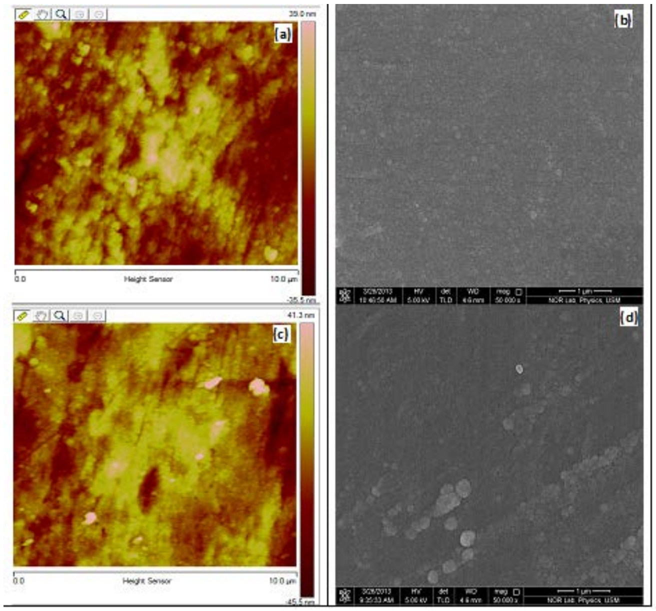

Fig. 3. Surface morphology of 400 nm Al_2O_3 thin film (a & b) before annealing and (c & d) after annealing

In order to get more information on surface parameters, the AFM images of both 400 and 500 nm thin film Al_2O_3 samples were processed using surface analysis software and the observed parameters such as surface roughness and particle size are summarized in Table – 2. The surface roughness does not show noticeable variation for different thicknesses and a major difference could be observed for 500 nm Al_2O_3 thin film samples when it is annealed at 300°C for 1 hr. From table - 2, the particle size of Al_2O_3 at 400 nm film thickness is higher than that of Al_2O_3 at 500 nm.

Moreover, it is understood that the smaller particles have high surface area than bigger particles and hence the contact surface area is maximum with smaller particles. This produce high contact resistance and will lead to poor thermal conductivity of such films. In our observation, 500 nm Al_2O_3 thin films have more resistance value than 400 nm Al_2O_3 since it has smaller particle size (0.28µm).

But, for annealed samples, there is no noticeable change in the resistance value since there is not much difference in the particle size observed between two thicknesses.

TABLE 2
SURFACE PARAMETERS OF AL_2O_3 THIN FILM DEPOSITED ON CU SUBSTRATES

	400 nm		**500 nm**	
	Non annealed	Annealed	Non annealed	Annealed
Roughness (nm)	9	9	8	136
Particle size (µm)	0.53	0.50	0.28	0.51

4 CONCLUSIONS

Al_2O_3 thin film at two different thicknesses is deposited on Cu substrate which was used as a heat sink for the given LED. The total thermal resistance and T_J were tested for different boundary conditions and a noticeable change are observed in both R_{th} and T_J for the given LED tested at 400 nm Al_2O_3 thin film boundary conditions. The annealing of Al_2O_3 thin film coated on Cu substrates was not supporting on decreasing total thermal resistance of the given LED. The surface analysis was evidenced to understand the restriction on heat flow for various surface roughness and grain size of the prepared Al_2O_3 thin film. From the observation, Al_2O_3 thin film coated Cu substrates did not show much influence on reducing the R_{th} and T_J for high power LEDs.

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