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AlN thin Film Coated Cu Substrates as Heat Sink for High Power LED Applications

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Abstract

Heat generates from power electronics must be dissipated to maintain operating temperatures within specification. Thermal management is an important design consideration in which thermal interface material (TIM) plays important role on reducing the thermal resistance between hot and cold points. AlN thin film and AlN/Al stack were used as TIM and Cu substrates was used as heat sink. The observed total thermal resistance ($R_{th\text{-}tot}$) was low for AlN thin film coated Cu substrate. Noticeable decrease in junction temperature (T_J) rise ($\Delta T_J = 6$ °C) was recorded for the LED using AlN thin film as TIM. AlN and AlN/Al thin film stack were not supported to enhance the luminosity of the given 3W LED but driving current influenced on optical properties noticeably.

Keywords: LED, AlN, thin film stack, thermal interface material, thermal properties, optical properties.

Introduction

Demand for most electronic products requires smaller packages with higher performance and more functions than the preceding generation. The increased thermal performance required of these smaller parts is mandatory to producing high efficiency, reduced sized systems. Significant increase in output power and die-level dissipation within the same footprint presents a challenge for controlling device junction temperatures. If thermal resistance is not effectively addressed, device junction temperatures can easily exceed levels that affect reliability.

In packages using thermal grease as the conducting medium between the die and the thermal solution, grease pump-out during operation of the part is a known failure mechanism[1]. Traditionally the power cycle test is a direct method to examine grease reliability. However, it is a time consuming process due to its long heating and cooling times. In order to avoid such pumping out issue, thin film based material has been suggested as thermal interface material.

Thermal conductivity of dielectric film is a key property of power devices, since it could substantially affect safety, reliability and performances. For thermal management issues, there is an increasing need to replace the dielectrics which is having poor thermal conductivity with the materials exhibiting higher thermal conductivity. In that respect, aluminium nitride (AlN) seems a good candidate. Thermal conductivity of single crystal AlN at room temperature has been reported equal to 320Wm^{-1} K^{-1} [2]. The high thermal conductivity and high dielectric constant of AlN are major factors favoring its use as a heat spreader material for electronic applications. Generally, thermal conductivity of deposited thin films is different from their bulk form due to the special nature of the microstructure resulting from the growth process. The thermal Conductivity can be affected by crystalline phases, crystallite sizes and structural imperfections such as impurities and lattice defects[2–6].

Various heat spreaders have been reported CVD diamond, Cu-W, AI-Sic etc,[7,8]. The diamond on Si and diamond on AIN have achieved excellent performance for the heat spreaders of laser diodes and microwave power FER, etc. In this work, AlN thin film coated Cu substrates are used as heat sink and the influence of Al thin film as stack with AlN thin film on the thermal properties of given LED also tested using dual interface method. In addition, the optical properties are also verified at various thermal interface material conditions.

Experimental Technique

AlN and AlN/Al thin film stack preparations

The synthesis methodology of AlN and AlN/Al stack was already reported in another work by the same author [9]. In brief, AlN and AlN/Al (AlN/Al/AlN/Al/AlN) stack thin film were deposited on Cu (23cm x 25 cm) substrates using pure Al (99.99% purity) target by DC reactive sputtering (Edwards make, Model-Auto 500) at room temperature. High pure Ar (99.999%) and N_2 (99.999%) were fixed at ratio of 80:20 (16 sccm : 4 sccm with total of 20 sccm) for AlN coating. In order to prepare stack, AlN and Al were stacked in the sequence of AlN/Al/AlN/Al/AlN on Cu substrate. Here after, AlN/Al stack represents AlN/Al/AlN/Al/AlN stack throughout this manuscript. To compare, the thickness of AlN and AlN/Al stack was kept constant as 800 nm and the individual thickness of thin film layers in AlN/Al stack was prepared accordingly. The cleaned substrates were loaded in the vacuum chamber and the coating was carried at 0.6 Å / sec deposition rate and 300 W sputtering power. The thickness of each stack was monitored anc controlled by digital thickness monitor. All thin films were coated at chamber pressure of 8.2 x 10^{-3}. To get the uniform thickness, rotary drive system was used and 25 RPM was fixed for stack preparation. Substrate to target distance of 7 cm was kept constant for all depositions.

Thermal transient and optical analysis

In order to test the performance of AlN and AlN/Al stack coated Cu substrate, thermal transient curve was captured based on the electrical test method JEDEC JESD-51 for 3W green LED package and analyzed. The experiment was carried out using Thermal Transient Tester (T3Ster) in still air box. Artic Alumina thermal paste kit was used as thermal paste to study the thermal behavior for comparison.

Calibration process was performed for the given LED and measured 2.289 as K-factor[10]. Three difference driving currents (100 mA, 350mA and 700 mA) was used to study the performance and the test was carried in a still-air chamber at room temperature of 24˚C ± 1 ˚C. The LED was forward biased for 900s and the transient cooling curve of heat flow from the LED package was captured for another 900s. The obtained cooling profile of the LED was processed for structure functions using Trister Master Software.

MK350 LED meter (Make: UPRtek) was used to record the optical parameters such as CCT, Color Rendering Index (CRI), and brightness (Lux). The performance of prepared AlN/Al stack thin film as TIM for 3W green LED package attached with MCPCB was also compared with the thermal paste applied Cu substrates.

Results and Discussion

Thermal performance using dual interface method

Thermal transient curve for all different boundary conditions was recorded at different driving currents using dual interface method. The cooling curve also was also recorded and the observed rise in junction temperature (T_J) is plotted for various boundary conditions with respect to driving currents as given in Fig. 1. It reveals that the AlN thin film coated on Cu substrates shows low value in T_J when compared to AlN/Al stack. Moreover, AlN/Al stack performs well compared with thermal paste (TP) applied Cu substrates. Even though, the observed ΔT_J (6.3 °C) is high for AlN thin film at 700 mA when compared with bare Cu substrates. But the ΔT_J is low as 3 °C for AlN/Al stack at 700 mA.

AlN itself a ceramic material and also very good thermal conductor and its conducting behavior diminish by doping or adding other elements. In our case, Al is stacked with AlN thin film and forms a complex structure as cermet. In cermet a coating, the thermal conduction is based on the phonon transfer which is due to the lack of free electrons and also AlN/Al has too many interfaces. Because of this several interfaces in cermet, the phonon scattering is possible and restrict the heat flow from the hot end to cold end as with driving current increases and hence T_J value for AlN/Al stack coated Cu substrates increases as with driving current increases at above 350 mA. As T_J increases, the availability of phonon in AlN/Al stack is further decreases and hence poor thermal conduction is possible.

This could be verified by measuring the total thermal resistance of the given LED for various materials as thermal interface at different driving current from the cumulative structure function. The observed cumulative structure function is presented in Fig. 2 (a-c). Fig. 2 clearly indicates that the thermal interface material plays important role on changing the cumulative structure functions as well as the total thermal resistance. The measured $R_{th\text{-}tot}$ at various driving currents is plotted in Fig. 3 and depicts that the AlN thin film coated Cu substrates show lower $R_{th\text{-}tot}$ than other interfaces. As observed with T_J, the $R_{th\text{-}tot}$ of AlN/Al stack is comparatively low at 700 mA than that of bare and thermal paste applied Cu substrates.

There may be two reasons for this increased thermal resistance; i) the formation of no. of interfaces within the AlN/Al stack and (ii) thermal mismatch between the substrate and the AlN/Al stack. In AlN thin film coated Cu substrates, the number of interface formed is less when compared to AlN/Al stack prepared Cu substrates. The another reason may be the contact resistance of Cu with AlN thin film is comparatively low than with Al thin film since the Al thin film made contact with Cu substrate in the prepared stack. In this case, thermal mismatch is possible with AlN/Al stack.

In order to understand the interface material resistance, the interface resistance is also measured from the cumulative structure function (Fig.2) and the observed values are presented in Table -1. The presented values in Table – 1 reveals the values of thermal resistance of interface materials such as AlN and AlN/Al stack indirectly. Table – 1 clearly indicates that the AlN thin film shows low resistance than other interface materials (like air, thermal paste and AlN/Al stack).

Based on the observed results, AlN thin film conducts more heat than AlN/Al stack and hence AlN thin film showed low thermal resistance. On considering interface thermal resistance, the observed low value with AlN thin film may be due to the influence of crystallite size. The crystallite size of AlN thin film over Cu substrates was low when compared with AlN thin film grown on Al substrates[11].

Optical properties

The influence of AlN thin film and AlN/Al stack as thermal interface materials on optical properties of given LED was tested and the data were recorded for 15 mins burning time at various driving currents. The variation in correlated color temperature with respect to measuring time as well as driving currents is given in Fig. 4. It clearly shows that the variation in CCT values is high for 700 mA. In addition, AlN thin film shows high values and AlN/Al stack shows low values for all driving currents. But it is also noticed that the variation in CCT is also high for the LED driven at 700 mA. Huge difference in CCT values could also be observed at high driving current (700 mA). The interface materials will affect the heat flow and hence the brightness of the LED will get diminish. To study this behavior, the luminosity of the LED is tested for various boundary conditions as well as driving currents. The observed results are plotted in Fig. 5. It reveals that the AlN/Al stack performs well at low driving current (100 mA) and diminish its thermal properties as the driving current increases since the temperature of the die increases and hence the interface temperature increases. As a result, the lux value decreases as very low when compared to bare substrate. Overall, the AlN thin film and AlN/Al stack performs poor at high driving currents.

The other optical properties such as color rendering index and peak wavelength was also tested for the given LED for various boundary conditions at difference driving currents. The data are collected while burning the LED for about 15 min. the observed CRI values are in between 8 – 16 for AlN/Al stack used as thermal interface material. From the observed CRI values, AlN/Al stack and AlN thin film does not show much influence and only changes are based on the driving currents. Since the observed CRI values are in the range between ± 4, the detailed discussion on this CRI value not necessary [12]. Based on this, it is concluded that the thermal interface material based on AlN thin film and AlN/Al stack will not affect the color rendering and retain its own color.

Conclusion

AlN and AlN/Al stack were prepared on Cu substrates and used as heat sink for 3W green LED. The observed total thermal resistance was low for AlN coated substrate and hence noticeable reduction in junction temperature was observed at high driving currents. Al thin film stacked with AlN thin film was aided to increase the R_{th} as well as T_J value noticeably. Significant improvement on optical properties such as CCT and lux was not observed for various driving currents. From the observed results, it is concluded that the AlN thin film coated Cu substrates can be used as heat sink for high power LED applications.

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Figure captions

Fig. 1 Variation in Junction Temperature rise of 3W green LED with respect to various interface boundary conditions measured at different driving currents

Fig. 2 Cumulative structure function of 3W green LED for various interface boundary conditions recorded at (a) 100 mA, (b) 350 mA and (c) 700 mA

Fig. 3 Variation in Total thermal resistance of 3W green LED with respect to various interface boundary conditions measured at different driving currents

Fig. 4 Variation of correlated color temperature of 3W green LED fixed on AlN and AlN/Al stack coated Cu substrates at various driving currents

Fig. 5 Variation of Luminosity of 3W green LED fixed on AlN and AlN/Al stack coated Cu substrates at various driving currents

Table 1. Interfacial Thermal resistance (K/W) measured from cumulative structure functions at various driving currents.

Driving Current (mA)	100	350	700
LED/Cu Sub.	38.35	37.72	35.32
LED/TP/Cu Sub.	38.06	36.87	35.89
LED/AlN/Cu Sub.	36.42	35.80	33.05
LED/AlN/Al stack/Cu Sub.	37.34	36.66	34.64

Fig. 1

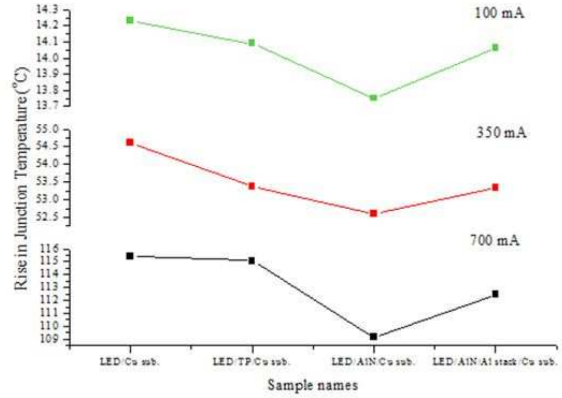

Fig. 2

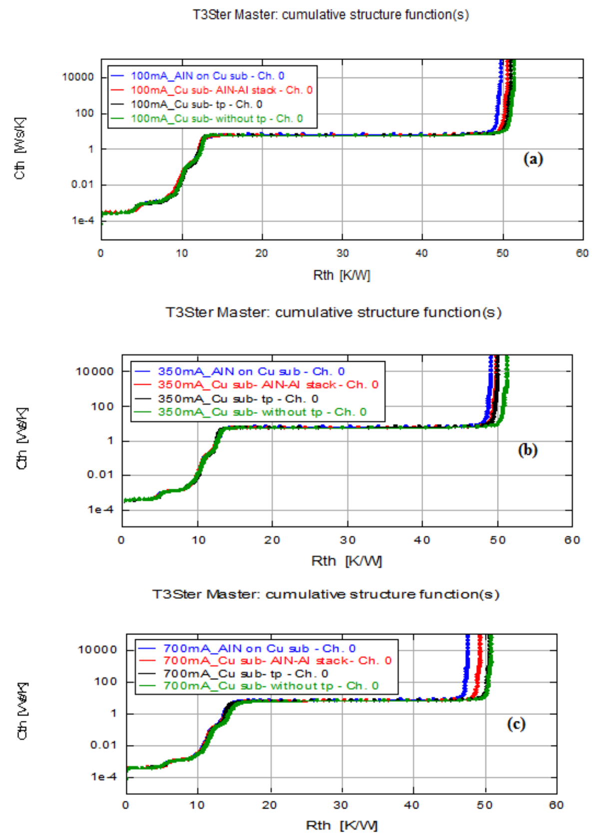

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Fig. 3

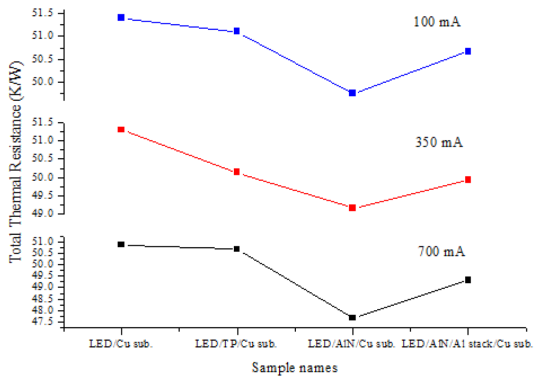

Fig. 4

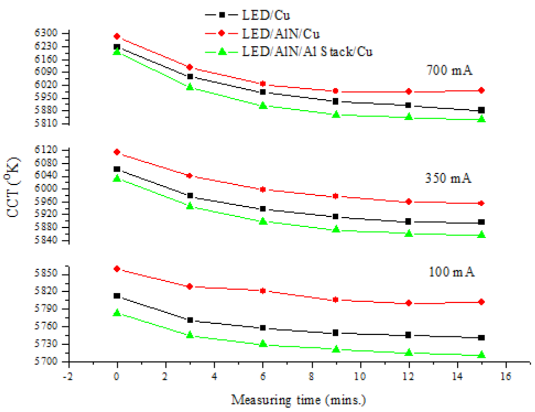

Fig. 5