IMPACT OF TEMPERATURE, PRESSURE, AND CURRENT ON THERMAL RESISTANCE OF THERMAL INTERFACE MATERIAL IN OPTOELECTRONICS DEVICE

J. W. MAH*, S. SHANMUGAN, D. MUTHARASU
Nano-optoelectronics Research Laboratory (NOR), School of Physics, University Sains Malaysia, 11800 Penang, Malaysia

The impact of various applied temperatures, pressures, and driving currents on the screen-printed dielectric thick film is discussed in this paper. The screen-printed dielectric thick film is treated as thermal interface material (TIM) that draws heat out from the heat source. The experimental setup has been modified based on the conventional ASTM 5470 standard where the thermal transient response of the dielectric layer is investigated. Bare and screen-printed substrates are heated up by MOSFET (heat source) at two different driving currents (0.5A and 1A). The dependency of either temperature (25°C to 55°C) or pressure (1 bar to 4 bar) measurement towards the thermal resistance of the dielectric thick film is measured by Thermal Transient Tester (T3ster). The total thermal resistance of both bare and screen-printed substrates are found to decrease with the increasing of pressure at constant temperature for all driven currents. This signifies that the thermal resistance of the dielectric layer is more dependenton pressure. In addition, the pressure applied to the dielectric layer serves to facilitate the longitudinal heat flow to the substrate. Variations in temperature has a less significant effect on the performance of dielectric layer compared to the variation in pressure.

(Received February 16, 2017; Accepted April 12, 2017)

Keywords: Resistivity Measurement, Thermal Interface Material, Screen-Printing, Dielectric Films, Thermal Transient Analysis

1. Introduction

WITH the rapid development and miniaturization of semiconductor devices, especially in light emitting diode (LED), the amount of accumulated heat has tremendously increased. A thermal solution for this problem has recourse to a higher thermal conductivity of thermal interface material (TIM) that can be extensively used in many microelectronics industries. In semiconductor package, the uneven surface of Metal-Core Printed Circuit Board (MCPCB) and heat sink creates a small gap when it made contact each other. This small gap has further contribution in the increase of thermal resistivity of the whole device's package. Thus, TIM has been used to fill up the gap so that the incomplete contact of the two surfaces can be reduced and improved thermal dissipation [1-4]. However, low thermal conductivity and thickness variation of pad type TIM in the existing market cannot solve the above said problem. To produce higher thermal conductivity material with low manufacturing cost, glassy type dielectric paste is synthesized and printed on the substrate by using screen printing method as shown in Fig. 1. The schematic diagram of the optoelectronics device shows the dielectric layer (yellow), which acts as thermal interface material (TIM) layer in the package. The LED package is attached on the circuit (red) layer via solder reflow process. A silver thick pad (dark blue) is printed under the LED package for creating a direct thermal path to the substrate (blue).Wang Feng et al. [5] used this printing method to study the dielectric properties of the $(Ba_{0.85}Ca_{0.15})(Zr_{0.1}Ti_{0.9})O_3$ (BCZT) thick film. He concluded that the produced thick film showed outstanding performance especially in micro actuator application. Furthermore, Xiao-Fei et al. [6] prepared the screen-printed thick film from superfine $Ba_xSr_{1-x}TiO_3$ powder.

*Corresponding authors: jianwen_mah@yahoo.com

They investigated and compared the dielectric properties of their sample with dense ceramic specimen. They were also concluded that the porosity of the sample significantly affected the microstructure which was related directly to the dielectric properties itself. Similar studies were carried out by many institutes to investigate the porosity, ferroelectric and piezoelectric properties of the screen-printed thick film whereas most of the researches suggested that screen printing method is a preferable method for low cost production of microelectronics application [7-9].

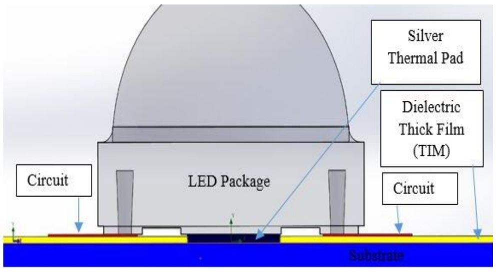


Fig. 1: Schematic diagram of thick film substrate mounted with LED as a package via screen printing process.

Conventionally, ASTM D5470 standard is used to measure the thermal conductivity of a material, where this test method is applied for getting the thermal transmission properties of dielectric material. In an experiment reported by Kevin Hanson [10], he modified the ASTM D5470 standard to control and monitor the specimen thickness under test. He also used various temperatures that are fixed in his experiment so that multiple layers of thermal resistance of the specimen can be obtained. Rao et al. [11] measured the thermal conductivity of metal matrix composites at different temperatures and pressures. He concluded that the thermal contact conductivity increases as the pressure increases. Grujicic et al. [12] investigated the important of the heat transfer across the surface contact of the sample's layers which contributed to the improvement of the device's performance [12]. Gwinn and Webb [13] have discussed the optimum thermal conductivity measurement of various TIMs at different pressures. Same type of research workshasbeen carried out by many groups to investigate the effect of pressure on TIM [1]. However, Ren-Jeng et al. revealed that the thermal contact conductance increased with the increasing pressure of diamond film coating [15]. Nowadays, glassy type dielectric thick film is considered as TIM for high power LEDs and can lead for chip on board concept for electronic industry. So it is necessary to understand the thermal behavior of these kind of coating on various testing conditions such as pressure and temperature.

In this paper, we have prepared a glassy type dielectric thick film on Al substrate by screen printing method and further cured and annealed at optimum temperature. The optimization of the curing and annealing temperature are not discussed in this paper. The thermal behavior of dielectric thick film is performed at various pressures and temperatures by transient analysis using Thermal Transient Tester (T3ster, mentor Graphics) at two driving currents where the heat source is supplied by MOSFET.MOSFET is chosen as heat source instead of LED as 100% heat is dissipated compared to 70% heat from LED. Comparison is made between the bare and printed substrates based on the measurement of total thermal resistance in different testing conditions.

2. Experimental Work

2.1 Sample preparation

Industrial grade dielectric paste supplied from Heraeous Company was used in this study. The dielectric paste is screen-printed on an aluminium substrate of series 3003 with the dimension of 5.6cm (L) x 5.6cm (W) x 1.52mm (T). The composition of the dielectric paste is not revealeddue to intellectual property of the prepared paste. Before the screen printing process, the paste is thoroughly stirred with mechanical stirrer so as to ensure the homogeneity of paste. It is further put and pressed through a permeable screen. A squeegee blade drags the paste to and fro the screen and forces it to deposit on the substrate. After each print, the obtained film surface was scanned by microscope for void detection. If the void is detected on the printed film, subsequent printing process is repeated. The printed substrate with minimal voids is further cured at 125°C for 15 minutes in an oven. A high temperature firing step is performed afterwards in a five-zone furnace at 550°C for 3 hours. The firing temperature has been fixed at 550°C due to the melting of aluminium substrate where efficient diffusion happens between the dielectric material and the substrate. The thickness of fired film is then measured by cyberScan Vantage 50 and observed an average thickness of 100± 2.00µm [16].

2.2 K-Factor measurement and thermal transient analysis

To measure the sensitivity of the MOSFET, K-Factor calibration on MOSFET is carried out by using Thermal Transient Tester (T3ster, Mentor Graphics). Initially, it is powered with 1mA of sensor current while heating it up with the temperature ranging from 20°C to 80°C, with temperature step of 5°C. In theory, K-Factor is defined as the correlation of the forward voltage and temperature difference at constant current, as described by the following equation (1) [17], where ΔT defines the change of temperature-controlled calibration environment with ambient temperature, ΔV_f, is the difference of the forward voltage**.**

$$K = \frac{\Delta T}{\Delta V_f} \tag{1}$$

As illustrated in Fig. 2, the experimental setup is structured according to the conventional experimental procedure as stated in ASTM 5460 standard. The setup directs the flow of the heat flux in one direction, creating a temperature gradient from the MOSFET (heating element) to the water-circulated cold water. A flat surface plate is placed on top of the MOSFET as an insulation layer for ensuring the heat flux flows downwards. With the aid of Pneumatic Thermal Interface material Tester (TTF-100), uniform pressure is continuously applied on the sample where the pressure is manipulated by a compressor. Throughout the experiment, the temperature of the cold plate is maintained by Julabo F12 circulator.

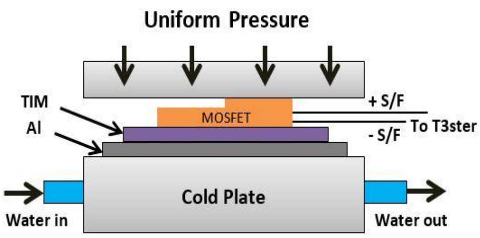


Fig. 2 Schematic diagram of Experimental setup

To initiate the thermal transient measurement, the MOSFET is attached on a bare Al substrate and powered up with 500mA of emission current, I_E, at room temperature and pressure. The reason of choosing this 500mA of emission current as starting current is due to the current lies in the middle range of high driving current that commonly applied in LED devices. After powering the MOSFET for 90s, it is left for 360s for performing cooling transient measurement. Additionally, the duration of cooling transient measurement has been optimized with several trials until the MOSFET reaches thermal equilibrium within the setup. The bare Al substrate is then replaced with dielectric printed Al substrate. Similar experimental procedure is repeated at room temperature and pressure. The results of both bare substrate and coated dielectric substrate are processed with T3ster Master post-processing software supplied by Mentor Graphics. The difference in the results between the bare and coated substrates represents the thermal resistance of printed dielectric thick film.

In the direction of further investigate the behavior of the dielectric thick film for various operating conditions, the bare substrate and dielectric printed substrateare tested from the room temperature, 25°C until 55°C, with temperature step of 10°C at constant atmospheric pressure and 500mA of driving current. To minimize the probability of thermal shock during the experiment, an interval of 10 minutes is applied for each measurement.After measuring the temperature dependence of both bare and coated substrate, the applied pressure is changed from atmospheric pressure (1 bar) to 4 bar, with pressure step of 1 bar at each constant temperature. In this experiment, the compressor used can only provide maximum pressure of 4 bar. Thus, further increasing of pressure will damage the tubing of the compressor and the testing fixture. Furthermore, for most of the LED related products, normal room temperature and pressure are exposed. However, if the LED products are used for application under high pressure and temperature, the performance of effective heat transfer out from the package is highly affected. Next, both temperature and pressure dependency measurements are further characterized with 1000 mA of emission current. Subsequently, this high driving current of 1A is chosen as it is widely used in most of the high power LED application, like spotlight and street light. Therefore, the thermal performance of the devices is deeply investigated. Similar experimental procedures are repeated so that the total thermal resistance of the dielectric thick film can be compared.In this experiment, the cooling transient measurement, either in temperature or pressure dependency measurement, is maintained at 1mA of sensor current. From JEDEC standard 51-1 [18], the thermal resistance of the device under test is characterized with electrical test method.

3. Results and Discussion

3.1 Pressure dependency measurement

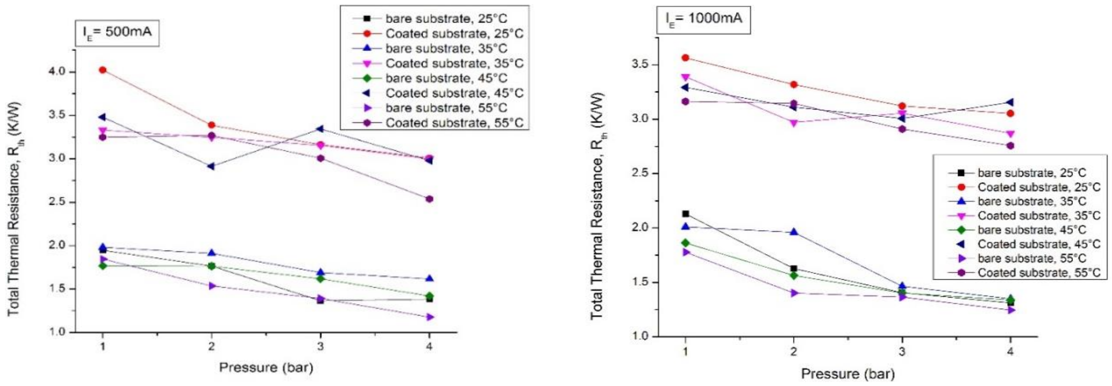
The K-factor of the MOSFET is calibrated to be 2.428 mV/°C prior to characterization of the dielectric thick film. The total thermal resistances of both bare and dielectric printed substrates subjected to driving currents of 500mA and 1000mA are shown in Fig. 3a and 3b respectively. It is clearly observed that there is a decreasing trend of total thermal resistance of both bare and dielectricprinted substrates with respect to increasing applied pressure [19]. In Fig.3a, the most significant drop of thermal resistance of the dielectric thick film is observed at room temperature of 25°C with applied pressure from 1 bar to 2 bar at 500mA. This phenomenon is mainly due to the reduction of interfacial gap between the heat source and the surface of dielectric layer,which accumulate in an efficient thermal transfer path towards the substrate.The further increment of applied pressure to the dielectric layer serves to create a more efficient longitudinal heat flow to the substrate [3-4]. However, the thermal dissipation efficiency of the dielectric layer is observed to saturate when the pressure is further increased from 3 bar to 4 bar under similar applied temperature. This shows that the dielectric layer has reached its maximum efficiency mechanically via compression. However, at the limit of maximum applied temperature of 55°C, the increasing pressure has shown less significant role in reducing the total thermal resistance of the dielectric layer. With the same increment in pressure from 1 bar to 2 bar, the thermal resistance is reduced considerably with the presence of dielectric layeras compared to the modest reduction in the case of bare substrate.

Next, the total thermal resistance shown in the Figure 3b (I_E=1000mA) has reported that under same applied temperature, the thermal resistance of the dielectric layer at higher pressure is nearly similar to the corresponding thermal resistance at 500mA. It is further observed that the total thermal resistance achieved at room temperature and pressure at 1000mA has been reduced to 3.563 K/W from the value of 4.022 K/W at 500mA. Compared to the total thermal resistance at room temperature and 1 bar, the same quantity of thermal resistance shows less drastic changes at higher temperatures of 35°C to 55°C when the current is increased from 500mA to 1000mA. The total thermal resistance of bare substrate shows nearly similar result for both applied currents at the higher temperature of 45°C and 55°C, as the resistivity of the metal is low. However, the thermal resistances at lower temperatures(25°C and 35°C) show higher values at 1000mA, comparing with the same quantity at 500mA under pressure of 1 bar.

3.2 Temperature dependency measurement

Apart from the pressure dependency measurement at different fixed temperatures and driving currents, similar methodology is applied to study the behavior of dielectric thick film with respect to temperature changes. At fixed pressure shown in Fig. 3, the total thermal resistance with the dielectric thick film coated Al substrates decreaseswhen the applied temperature is increased. This phenomenon implies that the dielectric layer has the capability to absorb more incoming heatand dissipates it to the ambient. However, at the maximum pressure of 4 bar and peak temperature of 55°C, the resistance of the dielectric drops significantly to 2.538 K/W from 3.249 K/W, the lowest values recorded in this study. For the case of bare substrate, the thermal dissipation is relatively insensitive to the increment of temperature.

When the driving current is doubled from 500mA to 1000mA, the total thermal resistance shows lower reduction with increasing temperature. Additionally, the effectiveness of increasing temperature for the reduction in thermal resistance at constant pressure is halved. Based on the experimental setup of ASTM D5470, the uncertainties of the measurement are possibly due to the distortion of the temperature gradient of MOSFET as a temperature sensor in this experiment [20]. This temperature distortion has the possibilities of affecting the uniformity of 1-D heat flux in the resistance measurement. Additionally, these uncertainties if the measurement are also caused by the positioning of the MOSFET after the cooling interval of 10 minutes due to manual positioning, which caused the total thermal resistance to be varied in this experiment. However, extreme caution of the positioning if the MOSFET has been taken into consideration during the measurement of thermal resistance of the samples.



a) b)

Fig. 3 Total thermal resistance of bare and coated substrates tested at different temperatures and pressure with driven current of a) 500mA b) 1000mA.

4. Conclusion

Thermal performance of the dielectric thick film deposited on Al substrateis tested using MOSFET as heat source with various pressures and temperatures. The observed thermal resistance of dielectric printed Al substrate is the lowest at high pressure of 4 bar and temperatures of 55°C for both driving currents. It is further concluded that the ambient temperature has less influence than pressure on the thermal resistance of thick film as thermal interface material. At room temperature with increasing pressure until 4 bar, thick film is suitable to be used in the semiconductor industries, as microelectronics or optoelectronics components. Uncertainties of the total thermal resistance of the thick film substrate are possibly caused by the distortion of temperature gradient of MOSFET as temperature sensor and the positioning of the temperature sensor in the experiment.

Acknowledgement

The authors would gratefully acknowledge the financial support and material provided by Collaborative Research in Engineering, Science and Technology (CREST), UniversitiSains Malaysia (USM), and Millennium Substrate Sdn. Bhd. (MSSB) under grant (304/PFIZIK/650696/C121).

References

[1] S. M. Wahid, C. V. Madhusudana, International Journal of heat and mass transfer, **46**, 4139 (2003).
[2] Jeng, Yeau-Ren, Jen-Tin Chen, Ching-Yang Cheng. Wear, **260**, 159 (2006).
[3] Yang, Ho-Soon, J.W. Kim, G.H. Park, C.S. Kim, K. Kyhm, S.R. Kim, K.C. KIM, K. S. Hong, ThermochimicaActa, **455**, 50 (2007).
[4] D. Schafer, Eisenmenger-Sittner, Mihai Chirtoc, P. Kijamnaksuk, N. Kornfeind, H. Hutter, E. Neubauer, M. Kitzmantel, Surface and Coating Technology, **205**, 3729 (2011).
[5] Bai, Wangfeng, Bo Shen, Fang Fu, JiweiZhai, Materials Letters, **83**, 20 (2012).
[6] Zhang, Xiao-Fei, Qing Xu, Di Zhan, Han-Xing Liu, Wen Chen, Duan-Ping Huang, Ceramics International, **38**, 3465 (2012).
[7] Almeida, Ana Fabiola Leite, P. B. A. Fechine, J. C. Goes, M. A. Valente, M. A. R. Miranda, Antonio Sergio B. Sombra, Materials Science and Engineering, **111**, 113 (2004).
[8] Lee, Sung-Gap, Chang-II Kim, Byung-Chul Kim, Journal of the European Ceramic Society, **24**, 157 (2004).
[9] Paul, Florian, Wolfgang Menesklou, Guido Link, Xianghui Zhou, JurgenhauBelt, Joachim R. Binder, Journal of the European Ceramic Society, **34**, 687 (2014).
[10] Hanson, Kevin, "ASTM D5470 TIM material testing", IEEE Twenty-second Annual In Semiconductor Thermal Measurement and Management Symposium, Symposium, pp 50-53, 2006.
[11] V. V. Rao. M. V. Krishna Murthy, J. Nagaraju, Composite Science and Technology, **64**, 2459 (2004).
[11] M. Grujicic, C.L. Zhao, E.C Dusel, , Applied Surface Science. **246**, 290 (2005).
[12] Gwinn, Joshua P., and R. L. Webb, Microelectronics Journal, **34**, 215 (2003).
[13] Jeng, Yeau-Ren, Jen-Tin Chen, Ching-Yang Cheng, Wear, **260**, 159 (2006).
[14] "Overview: Cyberscan Vantage 50" Application Note" [Online]. Available:http://www.cybertechnologies.com/wp/wp-content/uploads/vantage-50.pdf
[15] Implementation of the Measurement of Real Thermal Resistance and Impedance of Light-Emitting Diodes with Exposed Cooling, JEDEC 51-51, April 2012.
[16] Integrated Circuit Thermal Measurement Method-Electrical Test Method (Single Semiconductor Device), JEDEC [EIA/JESD 51-1], December 1995.
[17] Clemens J.M. Lasance and Andras Poppe, "Thermal Testing of LED," in Thermal Management for LED Applications, 1st ed. New York: Springer Science and Business Media, 2014, ch 4, pp 81-82.
[18] H. Masse, E. Arquis, D. Delaunay, S. Quilliet, P.H. Le. Bot, Internatinoaljournal of Heat and mass Transfer **47**(8), 2015 (2004).
[19] J. P. Gwinn, M. Saini, R. L. Webb, "Apparatus for accurate measurement of interface resistance of high performance thermal interface materials." In Thermal and Thermomechanical Phenomena in Electronics Systems IEEE ITHERM, The Eighth Intersociety Conference, pp 644-650, 2002.