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Low thermal resistance packaging for high power electronics

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Abstract

Alumina and aluminum nitride substrates are routinely used in micro-electronic packaging where large quantity of heat needs to be dissipated, such as in LED packaging, high power electronics and laser packaging. Heat management in high power electronics or LED's is crucial for their lifespan and reliability. The ever-increasing need for higher power keeps challenging the packaging engineers to become more sophisticated in their packaging.

With the availability of a 40 µm thick, high thermal conductivity ribbon alumina from Corning, the options available for packaging engineers has widened. This product has very high dielectric breakdown (~10kV at 40 µm thick), high thermal conductivity (>36 W/mK) and is rugged enough to be handled (with components attached) during packaging. These characteristics make ribbon alumina a cost-effective alternative to incumbent materials such as thick aluminum nitride, for use in high power microelectronics packaging.

In this paper, high power LED and IGBT modules are modeled using commercially available code from ANSYS®. A geometry representative of typical LED packaging and IGBT packaging is constructed with Ansys Design Modeler platform and the allied meshing is done employing in-built Meshing tool in ANSYS Workbench®. We show that packaging with ~40 µm ribbon alumina delivers performance on par with or better than packaging with thicker aluminum nitride substrates.

Key words

LED, IGBT, thermal resistance, junction temperature, packaging substrate

I. Introduction

A. Cooling of packages

Packaging for high power dissipation electronic devices such as LED and power semiconductors use ceramic sheet as a substrate material. Advances in the manufacture of these devices have made the devices smaller in size and capable of carrying higher power. In addition, packaging trends have called for sleeker and higher density packaging. These trends translate into higher heat generation in these devices and the need to keep the packaging within certain temperature limits, and at the same time call for a cost decrease.

The ceramic substrate is either used with a thin copper circuit layers typically made by plating copper on the substrate, called direct plated copper (DPC) or with thick copper layers, by directly bonding copper foils to the ceramic in a process called direct bonded ceramic (DBC). The DPC substrate is typically used for LED packages, while DBC substrate is used for power electronics packages, such as an insulated gate bipolar transistor (IGBT) etc. The DPC has a sputtered seed layer interface, typically a few hundred nanometers thick between the copper and the insulator, while DBC has a copper oxide-aluminum oxide solid solution at the interface.

The heat dissipated in the device is directly related to the thermal resistance of various materials in the thermal path. Since the focus of this paper is on the substrates, the thermal resistance of the various substrate materials is evaluated while keeping other materials in the thermal path constant. As the thermal resistance, by definition, is thickness over thermal conductivity, a thinner substrate with higher thermal conductivity would result in lower thermal resistance. The effect of this lower thermal resistance is studied in detail by modeling an LED package as well as an IGBT package.

B. *Options in use today*

The various substrate materials in use are compiled in Table 1. This table also includes materials that are bonded to copper by brazing.

Table 1 Substrate materials used in high power electronics packaging

	Thermal Conductivity W/mK	Typical thickness (μm)	Thermal Resistance (μK/W)	Dielectric breakdown (kV @ thickness)
96% Alumina [6]	24	250	10.4	3.6
Zirconia toughened alumina [3]	26	320	11.4	11.9
Aluminum nitride [3]	180	630	3.5	21.2
Beryllium oxide* [4]	325	1000	3.1	230
Silicon nitride [4]	90	320	3.6	14.9
Ribbon alumina	36	40	1.1	10.8

* AC dielectric strength

The thickness of ceramic substrate covers a range from 250 μm and above. The higher strength of some materials, such as ZTA and silicon nitride, allows it to be a little thinner than other substrates. The costs of more advanced materials such as AlN, Silicon nitride and Beryllium oxide can be several times higher than alumina.

C. *New option- Ribbon alumina*

There is a new substrate material available from Corning, an alumina sheet with a higher thermal conductivity and with high dielectric breakdown voltage shown in Figure 1. The properties of this ribbon alumina are listed in Table 1. Of these substrates, ribbon alumina has the lowest thermal resistance with high dielectric breakdown strength. This implies that high power modules operating at 1.2 kV can be built with ribbon alumina, even if it is only 40 μm thick. This is a substantial difference from the thicker ceramics available.

Figure 1 Ultra-thin alumina ceramic has thermal and electrical properties to enable a paradigm shift in power electronics packaging

The key concern in these high-power packages is to maintain a low enough semiconductor junction temperature. High junction temperatures decrease the life of the semiconductor, increase the failure rates. This study looks at how the ribbon alumina, when used in LED and IGBT packages decreases the junction temperatures through thermal modeling.

II. Model Development

A complete understanding of heat flow is essential for designing optimized packaging. Numerical modeling serves as an efficient tool for analyzing thermal flow inside the packaging assembly. In this paper, two different applications are modeled using commercially available code from ANSYS®, to demonstrate the benefits of packaging with ultra-thin alumina for high power LED packaging and IGBT packaging. A geometry representative of typical LED packaging and IGBT packaging is constructed with Ansys Design Modeler platform and the allied meshing is done employing in-built Meshing tool in ANSYS Workbench®. A three-dimensional thermal model is developed to investigate the performance and effectiveness of different substrates in removal of heat energy in LED as well as IGBT packaging units. A well posed steady state problem is solved by finding a solution to the formulated energy equation. An energy equation (Eq 1; first term equal to zero), primarily accounting for the conduction mode of heat transport is solved to evaluate temperature field across different components of a packaging unit.

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (v\rho h) = \nabla \cdot (k\nabla T) \tag{1}$$

where ρ is density of material (kg/m^3), h is sensible enthalpy given by $\int_{Tref}^{T} C_p dT$ where C_p is specific heat capacity, v is computed from motion specified for solid zone (v=0 in present study) and k is thermal conductivity of the material.

The solution to the energy equation helps in prediction of temperature distribution across various layers (components) in the packaging module. The predicted temperature field assists in computation of heat fluxes through different components (layers) in the packaging unit which can be employed to understand the heat flow inside the package. In addition to this, the numerical model also allows an estimate of optimum thickness of different components in a packaging unit. In both applications considered in this paper, packaging with ultra-thin alumina is compared with typical existing packages.

III. LED Packaging

A. *Geometry and details of the LED packaging units*

While there are different configurations in which LEDs are packaged, we focused on a generic version where the semiconductor is flip-chip bonded to the DPC ceramic substrate that is mounted on an insulated metal substrate (IMS). The electrical connections are given through copper filled vias in the substrate. A schematic of different thermal layers typically arranged in a LED packaging module is shown in Figure 2. A LED packaging module used in this study consists of a LED source which is thermally connected to copper through 5-micron thick Au-Sn solder. As indicated in Figure 2, the substrate is sandwiched between the upper and lower layers of Copper. A copper via passing through the substrate provides continuity between the low thermal resistance layers of upper and lower copper. A Sn-Ag-Cu (SAC) solder facilitates contact between lower copper layer and Bergquist HT07006 IMS which eventually leads the thermal energy to heat sink.

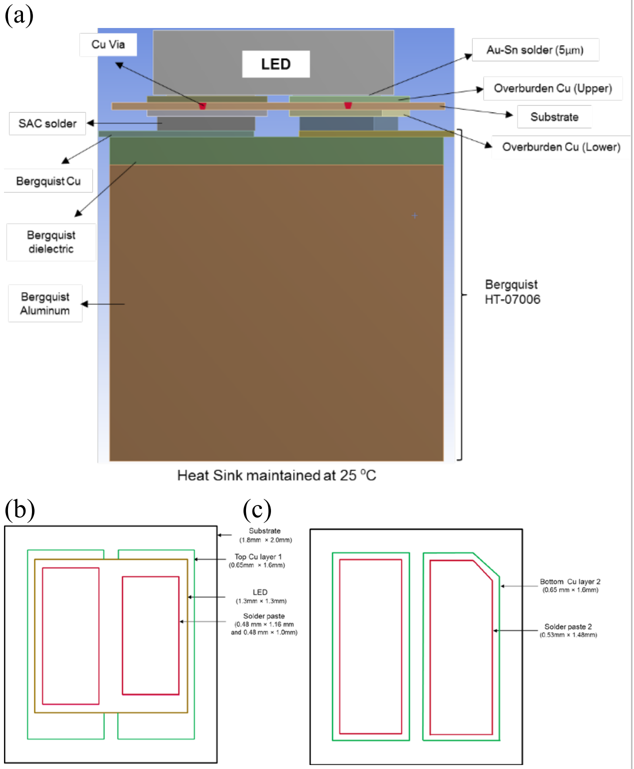


Figure 2 Schematic of LED packaging unit – sectional view of different layers of thermal resistances; (b) Top view representation of LED, solder paste, top copper and substrate layers; (c) Top view representation of bottom copper and solder paste.

B. Details of computational domain and boundary conditions

Simulations are carried out on a domain comprising of 12 -15 million tetrahedral/hexahedral highly refined computational elements. A power of 0.96W is supplied through the upper surface of the LED block shown in Figure 2. The bottom surface of the geometry which represents the heat sink is maintained at 25°C. Heat transport is assumed to be dominant in the vertical direction. Hence, a zero-flux boundary condition is imposed across the surfaces exposed to ambient conditions.

Junction temperature J_T is employed as the metric for evaluation of thermal performance of substrates used in packaging units across various configurations considered in this study. In case of the LED packaging unit, J_T refers to the maximum temperature observed across the horizontal plane at the middle of LED material.

C. Simulations performed for thermal analysis of LED packaging units

The thermal properties of various materials appearing in packaging designs is summarized in Table 2. Table 3 describes the various simulations performed to evaluate the effectiveness of different substrates in removing the heat from the LED source. Three substrates are considered viz. Alumina (Al_2O_3 – Cases 1 to 4); Aluminum Nitride (AlN - Cases 5 & 6) and Ribbon Alumina (RA – Cases 7 to 9). Through the above cases, the dependence of thermal performance of the packaging unit on via diameters, substrate type, substrate thickness and thickness of copper has been evaluated.

Table 2 Thermal properties of various materials used in the simulation

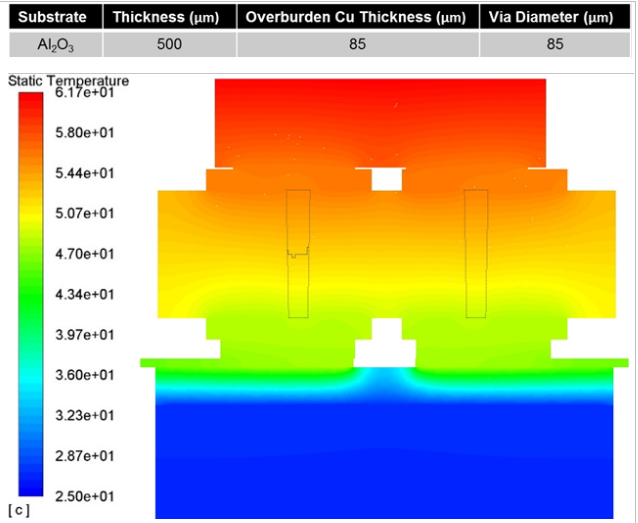
Material	Thermal Conductivity (W/m-K)	Thickness (μm)
Aluminum Nitride	180	-
Aluminum oxide	22	-
Ribbon alumina	36	40
Au-Sn	57	5
SAC Solder	60	200
Copper on substrate	385	25
Copper on Bergquist	385	35
Bergquist dielectric	2.2	150
Aluminum	205	1600
Sintered silver joint	240	10

Table 3 Cases simulated for thermal analysis of LED packaging unit

Case	Substrate	Substrate thickness (μm)	Cu thickness (μm)	Via diameter (μm)
1	Al_2O_3	500	85	85
2	Al_2O_3	500	75	85
3	Al_2O_3	500	65	85
4	Al_2O_3	250	75	75
5	AlN	500	85	85
6	AlN	250	75	75
7	R-Al_2O_3	40	25	40
8	R-Al_2O_3	80	25	40
9	R-Al_2O_3	40	25	80

D. Results and discussion

This section discusses the model predictions for thermal transport in LED packaging module. Figure 3 shows the temperature distributions across the vertical midplane slicing the package for alumina substrate. The grey line on the contour plot shows the location of copper via. In the following sections, the effect of various parameters will be examined in detail.



Substrate	Thickness (µm)	Overburden Cu Thickness (µm)	Via Diameter (µm)
Al_2O_3	500	85	85

Figure 3 Predicted temperature profile across mid vertical plane

1) Effect of Copper Thickness on Maximum Temperature across Junction Plane

The effect of copper thickness is investigated by considering three LED packaging configurations, represented by Cases 1, 2 and 3. Among these cases, the thickness of upper as well as lower copper layers are 85 µm, 75 µm and 65 µm respectively. All other geometrical aspects such as via diameter and thickness of other layers offering thermal resistance are kept constant. The maximum temperature across the junction plane for each case is shown in Figure 4. It can be observed that the junction temperature does not drastically change when the copper thickness is varied.

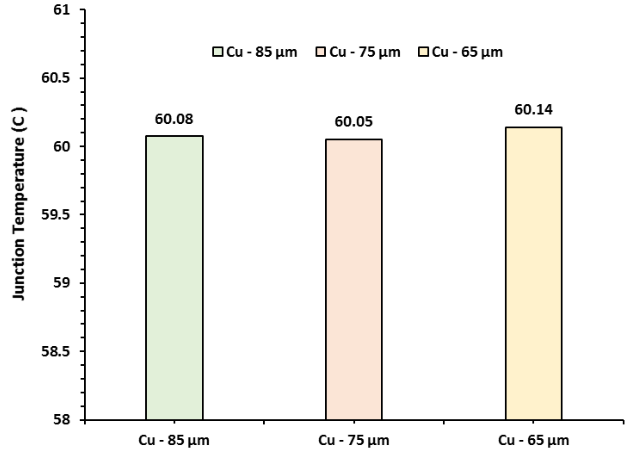


Figure 4 Effect of Cu thickness on J_T: Maximum temperature across Junction plane for Case 1, Case 2 and Case 3

2) Effect of substrate material on Maximum Temperature across Junction Plane

The dependence of junction temperature on substrate materials can be studied by examining Case 1, Case 5 and Case 7. As shown in Figure 5, the junction temperature is observed to be highest for Case 1, where the substrate is alumina (Al_2O_3). The thermal conductivity of alumina is lesser than AlN and ribbon alumina (RA) and hence 500 µm thick alumina offers much higher thermal resistance than its counterparts. Another interesting observation that stands out in Figure 4(a) is that a 40 µm ribbon alumina is able to remove heat as efficiently as by a thicker 500 µm AlN.

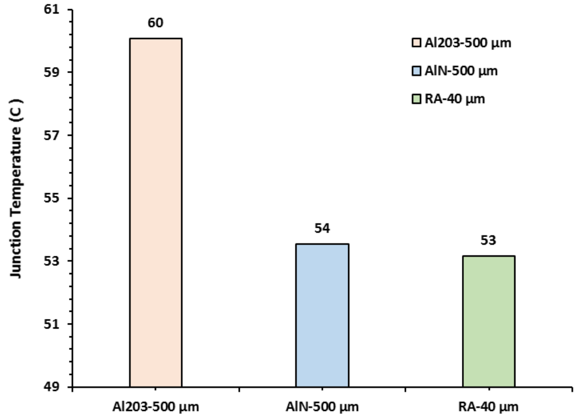
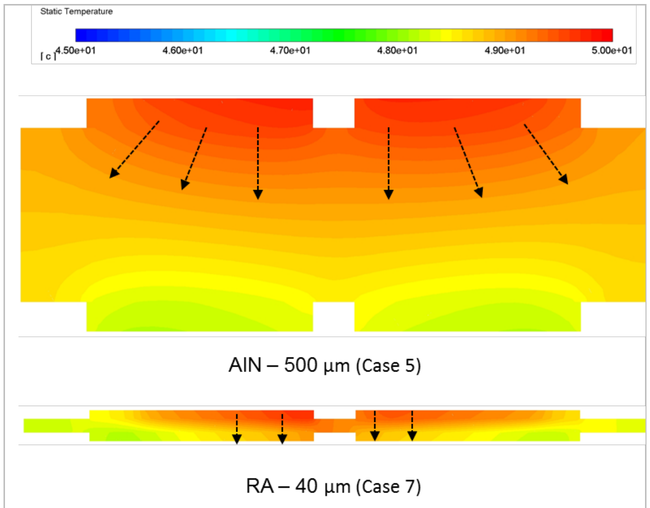


Figure 5 Effect of substrate material on J_T: (a) Maximum temperature across Junction plane for Case 1, Case 5 and Case 7



AlN – 500 µm (Case 5)

RA – 40 µm (Case 7)

Figure 6 Temperature distribution across longitudinal plane for Case 5 and Case 7.

Figure 6 shows the temperature distribution across the longitudinal plane (Upper Cu layer – substrate – Lower Cu layer) for Case 5 (AlN – 500 µm) and Case 7 (RA – 40 µm). The gradient across AlN substrate is much more pronounced than that across the ribbon alumina substrate suggesting that there is lesser resistance to heat transfer across the ribbon alumina substrate. There is certainly more spreading of heat in the lateral direction for AlN substrate (indicated by dashed arrows) that indicates a more efficient heat transfer. But in the end, the lower thermal resistance of the ribbon alumina substrate is more effective than lateral heat spreading in this case resulting in a lower junction temperature.

3) *Effect of Substrate Thickness on Maximum Temperature across Junction Plane*

In this section, the impact of substrate thickness on the junction temperature is discussed. LED packaging modules with alumina and RA substrates are considered. The thickness of alumina is decreased from 500 µm in Case 2 to 250 µm in Case 4, whereas in configurations with RA substrate thickness is varied from 40 µm (Case 7) to 80 µm (Case 8). The junction temperatures are depicted in Figure 7. It is evident that for both the materials, the thermal resistance increases with increase in thickness and hence the maximum temperature across the junction plane rises.

4) *Effect of Via diameter on Maximum Temperature across Junction Plane*

Via is a tapered conduit of copper across the substrate which may provide a low resistance path for transport of thermal energy. In this section, the effect of variation of diameter of via on J_T is investigated. Between Case 7 and Case 9 via diameter is doubled from 40 µm to 80 µm. The maximum temperature across the junction plane marginally drops from 53.1ºC to 52.9ºC as shown in Figure 8.

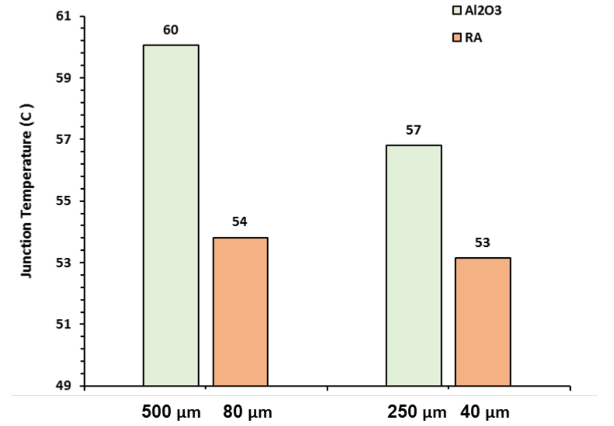


Figure 8 Effect of substrate thickness on JT: - Alumina substrate (500 and 250 µm thickness) and RA substrate (80 and 40 µm thickness)

Figure 9 summarizes the J_T predicted in LED for substrates employed across Cases 1 to 9 as a function of thermal resistance. The junction temperatures follow a near-linear change with respect the thermal resistance, indicating that the most important variable affecting J_T is the thermal resistance. All other variables such as the thickness of the copper layers, lateral heat flow, the size of the vias have minimal effects. It is also interesting that the impact of vias as a conductive pipe for heat dissipation is minimal. This could be because the area fraction occupied by the via is >100 times smaller than what is recommended for effective heat dissipation by a thermal via [2].

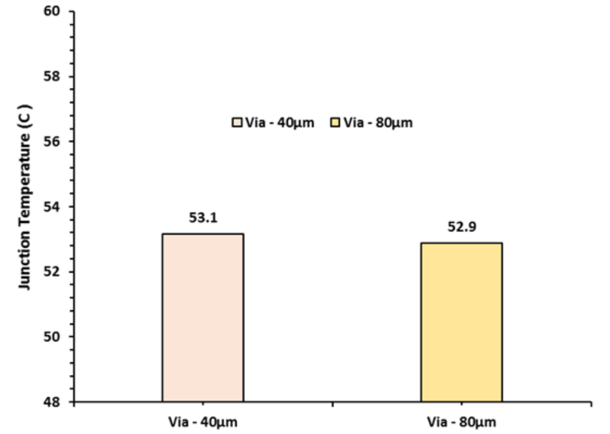


Figure 7 Effect of via thickness on J_T: Case 7 and Case 9 - RA substrate

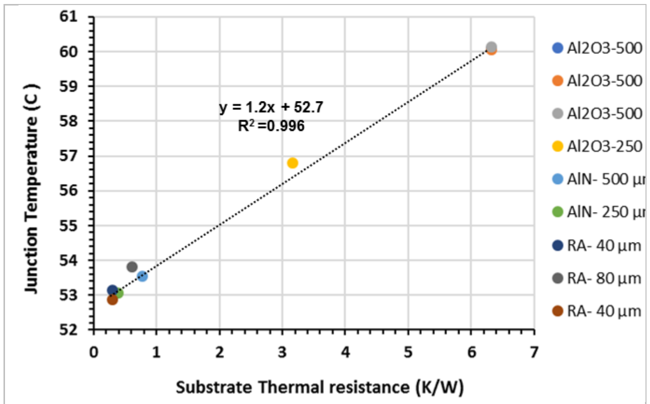
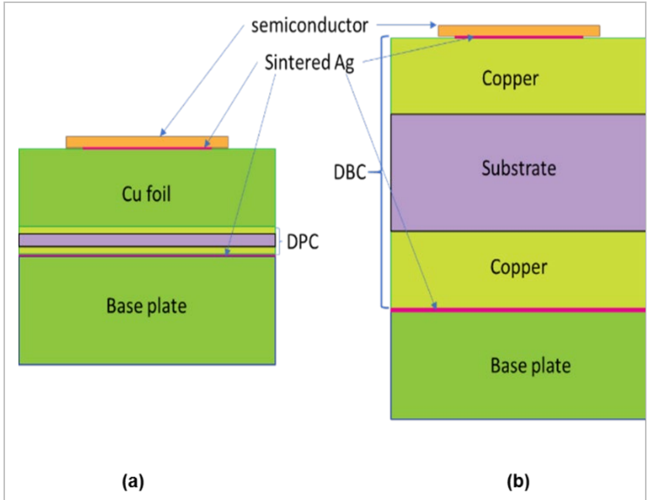


Figure 9 Junction Temperature observed for substrates in Cases 1 to 9

IV. IGBT Packaging

A. *Geometry and details of the IGBT packaging units*

For this study, the geometry and components considered in Ammous, et al [2] were used. A Semikron module SKM 75GB123D (75A/1200 V) structure was used to model IGBT. As explained in the next section, the power module with thick substrate is assembled as modeled by Ammous et al. [2], but the module with ribbon alumina was assembled in a different way that we think the thin brittle (earlier it's called robust) material can be handled.



(a) (b)

Figure 10 The detail in the heat flow path in (a) ribbon alumina-based module and (b) conventional module

The stack-up of various layers comprising the packaging units employed in this study are shown in Figure 10 (a) and (b). In the conventional design (Figure 10b), the IGBT module is soldered (AuSn) to the DBC substrate. Further, the DBC is connected to the baseplate through sintered silver.

Ribbon alumina-based module (Figure 10a) is assembled by sintering a DPC to a base plate, followed by attachment of a copper foil by thermo-compression bonding, followed by die attachment. This is different from the incumbent module where the module is first built on the DBC and then the DBC attached to the base plate. This change is important because the ribbon alumina may not be sturdy enough to withstand the handling during the DBC assembly process. Once the ribbon alumina-based DPC is secured to the base plate, it can be effectively handled. The actual assembly process has not been studied. This paper provides a "what if" scenario- what kind of benefits can we achieve if we solve the assembly aspects.

B. *Details of computational domain and boundary conditions*

The computational domain used in the simulations consists of high-resolution mesh with 10-15 million hybrid mesh elements (hexahedral /polyhedral). Two sets of simulation are performed. In the first case, the power source at the top face of IGBT is maintained at 1.2 kW and the bottom surface of the baseplate is held at 25ºC. The maximum temperature (J_T) at the uppermost face of the IGBT module is evaluated for packaging modules for different substrates. In the second case, the maximum temperature at junction face is kept constant at 150ºC and the corresponding power allowed by packaging module is computed. In the current study, it is assumed that heat losses to surrounding air media is negligible and hence has been ignored.

As in the earlier scenario, Junction temperature J_T is employed as the metric for evaluation of thermal performance of substrates used in packaging units across various configurations considered in this study. J_T corresponds to the maximum temperature (junction temperature) on the uppermost surface of the IGBT module, IGBT packaging device.

C. *Simulations performed for thermal analysis of IGBT packaging units*

Table 4 summarizes the different packaging designs considered in this study to highlight the advantages of ribbon-alumina substrate over incumbent materials such as aluminum nitride and alumina in IGBT packaging. Cases 1 and 2 correspond to the conventional packaging design with substrate material being AlN and Al_2O_3 respectively. Cases 3 and 4 cover the proposed packaging design based on DPC, with ribbon alumina substrate of 80 µm and 40 µm thickness respectively.

Table 4 Cases simulated for thermal analysis of IGBT packaging unit

		Thickness						
Case	Substrate	IGBT	Au-Sn solder	Copper upper	Substrate	Copper lower	Sintered Ag	Copper base
		(mm)	(µm)	(µm)	(µm)	(µm)	(µm)	(mm)
1	AlN	0.4	20	250	380	250	10	3
2	Al_2O_3	0.4	20	250	250	250	10	3
3	RA	0.4	20	275	80	25	10	3
4	RA	0.4	20	275	40	25	10	3

D. Results and discussion

The result from the first set of simulations, where a power source of 1.2 kW is applied at the top surface of the IGBT module is discussed in this section. The contour plot showing temperature distribution over the plane across which J_T is evaluated, is depicted in Figure 11. In cases where the heat transfer is efficient, such as in Figure 11(d), the corners appear cooler as the heat is conducted away. Also, there is more gradient from the edges to the center due to the same reason. Alumina, Figure 11(b), shows the poorest heat transfer.

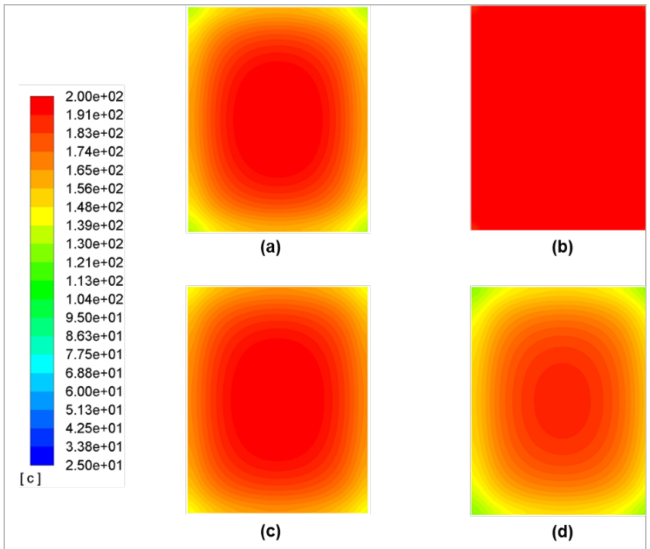


Figure 11 Temperature distribution across the surface of IGBT for packaging units with various substrates, (a) AlN; (b) Al2O3; (c) ribbon alumina (80 µm) and (d) ribbon alumina (40 µm)

This effect can be seen in a greater detail when observing the temperature contour plots across the longitudinal section spanning the IGBT and the substrate. As with LED, Figure 12 (d) shows lower gradient than Figure 12(a) indicating a more efficient heat transfer.

With the same boundary condition of 1.2kW imposed, the temperature of the top face predicted from the thermal model is shown in Figure 13 which indicates that the alumina substrate shows the highest temperature (321°C) and 40 µm RA shows the lowest (192°C). While 80 µm RA shows a J_T similar to 380 µm AlN, it is significantly higher than that predicted for 40 µm RA. If the minimum thickness of DBC substrate available with AlN substrate is 630 µm [5], the difference in J_T between AlN and 40 µm RA is expected to be higher than that predicted in this study.

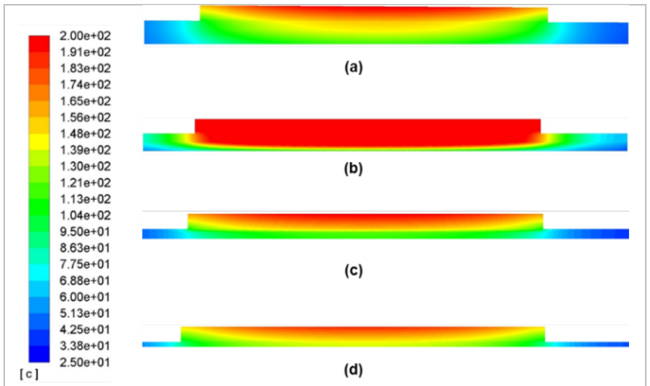


Figure 12 Temperature distribution across the longitudinal plane of IGBT and substrate for in various cases, (a) AlN ; (b) Al2O3 ; (c) ribbon alumina (80 µm) and (d) ribbon alumina (40 µm)

In practice, there is an allowable maximum temperature that the IGBT package has to be designed to. The choice of the substrate will be dictated by this maximum allowed temperature. In the second set of simulations, an attempt is made to evaluate maximum heat flux (power) allowed through the packaging material by when a constant temperature boundary condition of 150°C is maintained at the top face of the IGBT module. The results shown in Figure 14 clearly demonstrate that compared to thicker substrates, packaging with thinner ribbon alumina substrate can efficiently manage heat in IGBT's with much higher power rating (1050 W) while maintaining maximum allowable temperature of 150°C in the module.

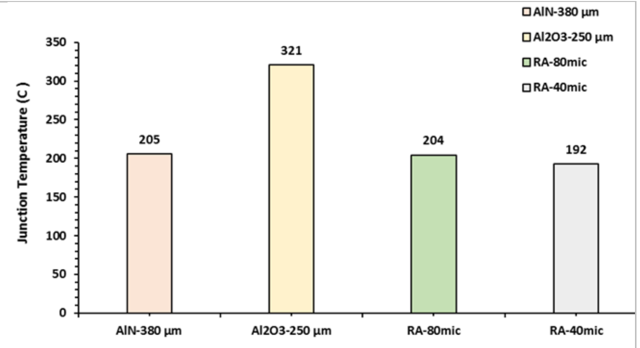


Figure 13 Maximum temperature J_T across the upper surface of IGBT (a) AlN; (b) Al2O3; (c) ribbon alumina (80 µm) and (d) ribbon alumina (40 µm)

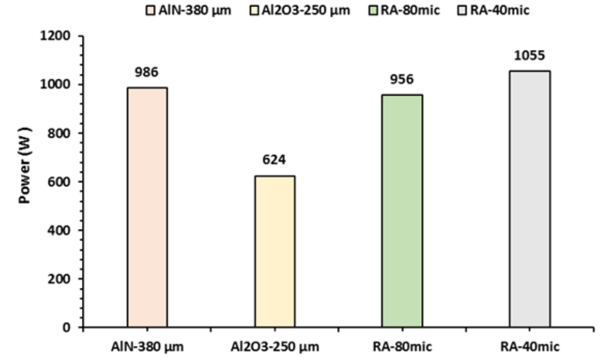


Figure 14 Maximum allowable power across the substrate of IGBT package with upper surface at 150°C (a) AlN; (b) Al2O3 ; (c) Ribbon alumina (80 µm) and (d) Ribbon alumina (40 µm)

Packaging considerations

E. Handleability of ribbon alumina

Ultra-thin alumina is in a form factor new to ceramic substrates. Thick ceramics are typically made in 4.5” × 4.5” size or 5” × 7” sizes. When it is thinned by lapping, it is usually in the 4.5” × 4.5” size. This just means that the thin ceramics needs to be handled differently than thick ceramics. Such thin brittle materials have been handled in other applications before. For example, a 2.94×3.37 m of 0.5-0.7 mm thin glass is routinely used in production of LCD TVs.

Due to the process used to manufacture this substrate, it is as stronger than conventional alumina and is as strong as conventional zirconia toughened alumina with strengths of >600 MPa. With an elastic modulus of about 380 GPa, the 40 µm thick parts are stiff enough to hold components and be easily handled after singulation.

There are ways to handle ribbon alumina substrates in the current packaging equipment. The description of which is beyond the scope of this paper. The reader should contact the authors to learn more about how to handle ribbon alumina and to design components using ribbon alumina.

F. Re-design package and its manufacture

As an example, an alternate component design and manufacturing process is used for the IGBT module wherein a 40 µm alumina substrate can be used with existing packaging equipment. The solution contemplated in this study is that a ribbon alumina-based DPC is bonded to the copper base plate by nano-silver sintering. A shaped foil of copper is attached to the top by Cu-Cu thermal compression bonding to provide low resistance current path. The IGBT die is attached to this foil and connections made. In such a process, the handling of a free-standing thin dielectric, in the form of DPC is minimized and the thickness of copper layer is made independent of the dielectric thickness. This is enabled since, even 40 µm thickness, the ribbon alumina has a high dielectric breakdown voltage.

Such a package has not been built so far. So, this paper is intended to show the benefit this unique ribbon alumina can have in high power electronic packages.

V. Conclusion

In the current study thermal modelling has been used to show that the predicted junction temperatures of LEDs packaged on 40 um thick ribbon alumina is about the same or better than that packaged on much thicker aluminum nitride. The predominant impact of this low junction temperature is due to the thermal resistance of the substrate. Other factors such as the thickness of copper circuits, size of vias and lateral flow in thicker substrates do not have much effect.

Thermal modelling was also used to show that the lower thermal resistance of 40 um ribbon alumina was able to conduct away heat more efficiently in IGBT packages, like in LED application. When the IGBT based on ribbon alumina is packaged differently than the conventional process for DBC-based package, this advantage of low thermal resistance can be exploited.

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