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Transient Thermal Simulation Analysis of Die-Attach Adhesives

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ABSTRACT

This paper discusses the approach of using a three-dimensional finite element analysis (FEA) model for transient thermal analysis of die-attach materials layers with the silicon carbide (SiC) diodes directly attached to the bonded copper. For FEA analysis, six different die-attach materials models were developed: Au/Sn (80/20) braze, nanoscale silver, SAC alloy solder paste, Epo-Tek P1011 epoxy, graphene, and copper. By evaluating the maximum temperature and total heat flux, FEA modeling can be utilized to identify which die-attach materials have more effect on the thermal conductivity of the model. Fourier's law of heat conduction was implemented to investigate transient thermal characteristics during heating with commercial software code, namely ANSYS. Temperature dependency and thermal material properties, and other thermal parameters boundary conditions were taken into consideration throughout the thermal conductivity procedure. The temperature and total heat flux distribution changes of the die-attach and substrate assemblies were obtained and transient thermal characteristics were analyzed during heating within 1.5 s by using temperature load, 90.3 °C on the dies (diode) surface. Moreover, heat flow was also measured in the model by comparing the thermal resistance discovered in the die-attach materials with a manual calculation. The graphene achieved the best results in terms of the least maximum temperature and total heat flux values, 90.3 °C and 11.04 x 10^6 W/m^2 respectively. As a result, graphene-based die-attach materials produce an efficient heat conductor, which can become beneficial in the future. This is due to the lowest thermal resistance and highest thermal conductivity of graphene die-attach materials.

Keywords: Die-attach materials, finite element analysis, transient thermal, thermal resistance, total heat flux

1. INTRODUCTION

A printed circuit is an electrical component in which the wiring and certain components are made up of a thin coat of electrically conductive material applied in a pattern on an insulating substrate using one of several graphic arts techniques. Printed electronics was originally envisioned as a low-cost alternative to silicon-based electronics, its complementary technology. Because printed materials get thinner, lighter, and more flexible as substrates become thinner, it is sufficient to integrate materials into existing production lines [1]. As the need for wearable gadgets and thinner electronics grows, printed electronics are being used to create flexible keyboards, antennas, electronic skin patches, and more. Power modules that can operate at high powers and frequencies, as well as have excellent integrability and downsizing capabilities, are in high demand [2].

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Die-attach adhesives are essential materials in the production of internal components for a wide range of electronic devices. With the decreasing size of electronic devices, the challenges of semiconductor and circuit board bonding are increasing. In order to ensure proper operation and wear resistance, such as sufficient adhesion between the die and the substrate (to prevent the die from detaching from the substrate), high electrical and thermal conductivities, suitable mechanical properties to avoid and support thermo-mechanical stresses, and a high melting point to ensure reliability in harsh environments are required [3]. Die-attach adhesives are important not only for the structural integrity of a semiconductor or circuit board but also for heat control and the improvement of electrical performance. The impact of interconnect failure materials on conductive filler failure rate grows dramatically as interconnect size and the number of interconnect layers' decreases. Such failures are also caused by semiconductors, such as SiC power modules, which are expected to function at temperatures beyond 175 °C, the physical limit of ordinary Si power chips [4]. Power electronic systems can be downsized due to the higher working temperature. The performance metrics and dependability of joints should be improved because the bonding layers are also exposed to such high temperatures.

The die-attach layer based on sintering of Ag nano-particles is a potential option as it has a low process temperature (< 300 °C) and a high operation temperature (due to the high Ag melting point (961 °C) [5]. Specific die-attach materials are thus a genuine issue in order to meet the criteria of high-temperature power electronics applications. As a result, several researchers throughout the world are working hard to find the best materials and processes for producing high-temperature die attachments. Heat dissipation is now one of the issues impeding the rapid development and widespread acceptance of multi-heat source power devices [6]. Gold-tin (Au-Sn), gold-germanium (Au-Ge), gold-silicon (Au-Si), silver glass, silver-indium (Ag-In), high lead (Pb) solutions, and nanoscale silver are among the high temperature applications of die-attach materials that have been researched. These high-temperature die-attach materials have been used in a wide range of industries and are continuously being developed [2].

Thermal resistance is a heat property and a measurement of how well an object or substance resists the heat flow. By offering low-contact thermal resistance, die-attach material plays an important role in the thermal management of high-power diode packages. Regardless of the package junction temperature or thermal resistance, the die-attach material's thermal conductivity is the most important parameter [7]. According to [8], Au/Sn bonding has the best mechanical and thermal properties than silver paste and solder paste materials because Au/Sn eutectic has the lowest contact thermal resistance. Interfacial thermal resistance, which results from weak phonon-phonon coupling and phonon backscattering at the boundary area, limits heat transfers in composite systems [9].

Graphene has recently been used as a nano-filler in polymers to improve mechanical, thermal, electrical, and functional properties. Because of its numerous appealing qualities, such as unique structural effects, high specific surface area, and high conductivity, graphene has the greatest potential to be used as a high-performance absorption material [10]. Due to its remarkable electrical, mechanical, and thermal capabilities, graphene as a filler has the potential to improve the performance, functionality, and durability of numerous applications for the future generation of electronic devices, composite materials, and energy storage devices [11]. Graphite is made by layering graphene. The Van der Waals forces are the interactions between different graphene layers. The graphene sheets are inherently stacked together due to strong van der Waals interactions between adjacent layers [1]. As the van der Waals bond strength increases, the interfacial thermal resistance of graphene decreases [12].

To calculate the maximum temperature and total heat flux, experimental results can be used as an input parameter for material properties in FEA modeling. The purpose of the study was to determine the dependability of the circuit at various types of die-attach materials, as well as the condition of the model at the thermal weak point, and to determine how different types of die-attach cause significant heat flow variance that can be calculated using the maximum temperature and total heat flux generated by FEA modeling. It is important to comprehend the properties of die-attach materials. Different die-attach materials will have a significant thermal effect on the results, and the effect of die-attach materials on temperature and total heat flow was explored in FEA analysis. However, data on the thermal dissipation caused by attachments, as well as the influence of different die-attach materials and toughness on thermal dissipation, were lacking. The transient thermal analysis can be used to optimize the transient of maximum temperature and maximum total heat flow during heating. Following the accomplishment of the above objectives, an attempt was made to discover the optimal die-attach materials with the lowest temperature and total heat flux as determined by FEA modeling.

2. METHODOLOGY

This study aimed to determine which die-attach materials would have the least amount of temperature and total heat flux. The lowest numerical results were then selected to analyze the time-dependent of the circuit. The FEA of the circuit was performed using numerical workbench tools. Circuits were designed in CATIA modeling software, then converted as an IGES file and imported into the workbench. After that, the model was fine-meshed, and then the tetrahedrons patch confirming method was used, in which the computation process was expected to take some time. Silicon carbide (SiC) diodes were subjected to time-varying loads and their maximum temperatures were observed with ANSYS transient thermal simulation.

2.1 Model Configuration

Data from previous studies and FEA models were used in the research including the graphene material properties, as well as simulated temperature and total heat flux values. The model was prepared with CATIA and then the file was saved in IGES format and imported into the workbench software as shown in Figure 1. In this work, a transient thermal analysis was carried out to investigate the temperature and total heat flux variation across the model layers by applying temperature load value on the dies using ANSYS. The model substrate material was copper and silicon carbide (SiC) diodes were attached directly to the bonded copper with die-attach materials. Die-attach is a type of adhesive or connector that connects the diode (die) to the substrate.

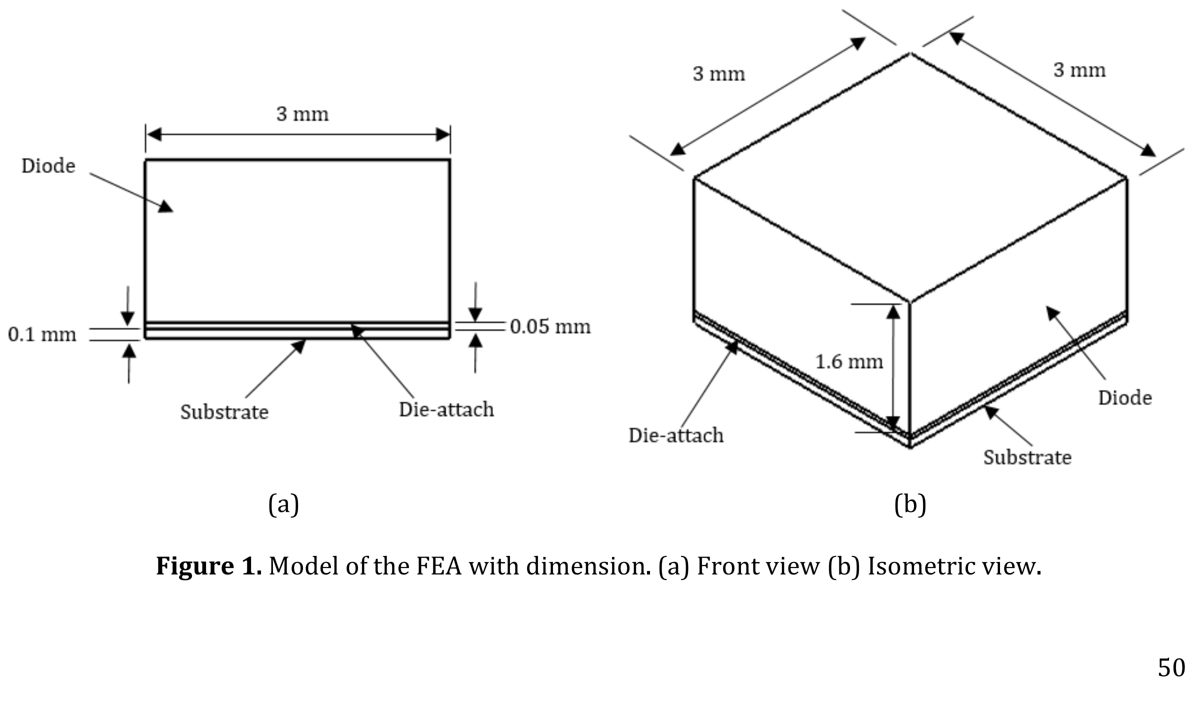


Figure 1. Model of the FEA with dimension. (a) Front view (b) Isometric view.

Three of the four die-attach materials being evaluated were metallic, with good heat transfer characteristics as well as good electrical conductivity. The fourth die-attach material was epoxy, although possesses good electrical properties, but has much lower thermal conductivity than the other materials.

2.2 Finite Element Analysis

The results were determined by numerically solving the governing equations at each node using a mesh-generated finite element approach. As shown in Figure 2, the fine mesh option with tetrahedrons patch confirming (TPC) method was used with the model preference, and the computation process took some time. The finite element was resulting in 44592 nodes and 24341 elements.

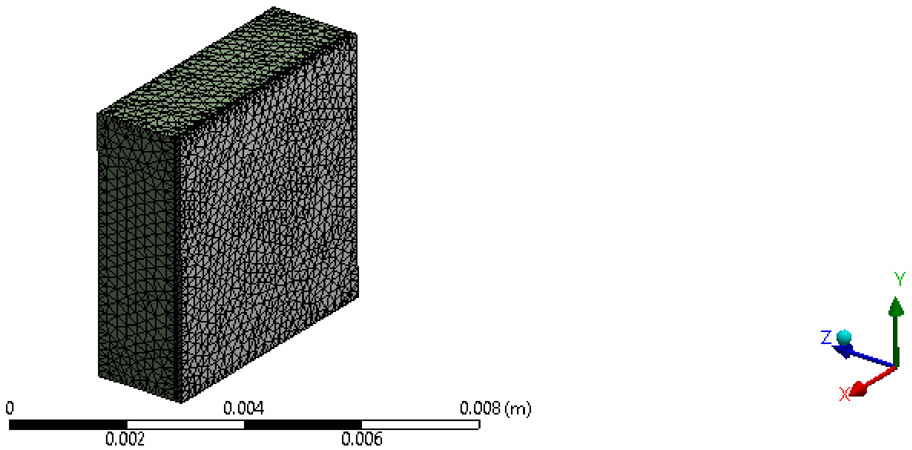


Figure 2. Mesh model of the die-attach sample.

FEA of conductive inks thermal analysis on a screen-printed model using ANSYS software was used to simulate the circuit's thermal behavior under heating load. The die-attach was approximated as a layered structure to imitate the screen-printing method. The study's purpose was to determine how different die-attach materials affected the diode and substrate resulting in heat flow. The focus of this research was to find out which die-attach materials are suitable for the whole model based on the least amount of total heat flux maximum values.

2.3 Boundary Conditions

The simulation began by defining the materials composing the model, along with their pertinent physical properties such as thermal conductivity, specific heat, and density. The circuit substrate was copper, the lands on the circuit were die-attach and the devices were silicon. Four die-attach materials' physical properties: Au/Sn (80/20) braze, nanoscale silver, SAC alloy solder paste, Epo-Tek P1011 epoxy, and maximum temperature performed on the diodes as semiconductor devices were used in this study [13] as references. The die-attach properties had already been discussed. Temperature and other thermal parameters varied over time in a transient thermal analysis were used to evaluate the structure in steady-state thermal conditions. In transient analysis, the induced loads were time functions that can be used to divide the load versus time curve into load steps [14]. The SiC dies were designated as a volume heat source. The maximum temperature of 90.3 ° C was applied to the SiC dies with metallic, carbon, and epoxy die-attach materials within 0.5-second intervals: t = 0.5 seconds, t = 1.0 seconds, and t = 1.5 seconds to compare the thermal conductivity values between all types of die-attach materials.

Heat flux is the rate of thermal energy flow per unit surface area of the heat transfer surface. In this study, the heat flux was applied to the SiC dies surface with metallic, carbon, and epoxy die-attach materials within 1.5 seconds to compare thermal conductivity values between all types of die-attach materials. From Equation (1), the total heat flux can be calculated on different die-attach materials circuits. The heat flux can be obtained by following Fourier's law of heat conduction [15]:

$$q'' = k\ (dT/dx) \tag{1}$$

where 'q"' is heat flux (W/m^2), 'k' and 'dT' is thermal conductivity coefficient (measured in W/m °K) and temperature of heat presents on the top surface of the diode (measured in Kelvin), respectively and 'dx' is the thickness of the materials (from the top surface of the diode to the bottom surface of the substrate).

Figure 3(b) shows R_1, R_2, and R_3 representing diode, die-attach material, and copper substrate, respectively. These three materials are the resistances when the load is applied to the diode. To acquire the total heat flux values of the model, the heat is transferred from the diode through the die-attach material, copper substrate, and finally to the surrounding temperature of 24 ° C. The simulated total heat flux value from ANSYS is compared to the calculated total heat flux value. Figure 3 illustrates a schematic diagram of heat flows in the model. As illustrated in Figure 3(b), material resistance, R is given by the following;

$$\mathrm{R} = \frac{dx}{\mathrm{k}} \tag{2}$$

where 'dx' is the thickness of the materials and 'k' is material thermal conductivity.

By using the series method, the heat flux can be obtained by following;

$$q'' = \frac{\Delta T}{R_1 + R_2 + R_3} \tag{3}$$

where ΔT is the temperature difference across the materials.

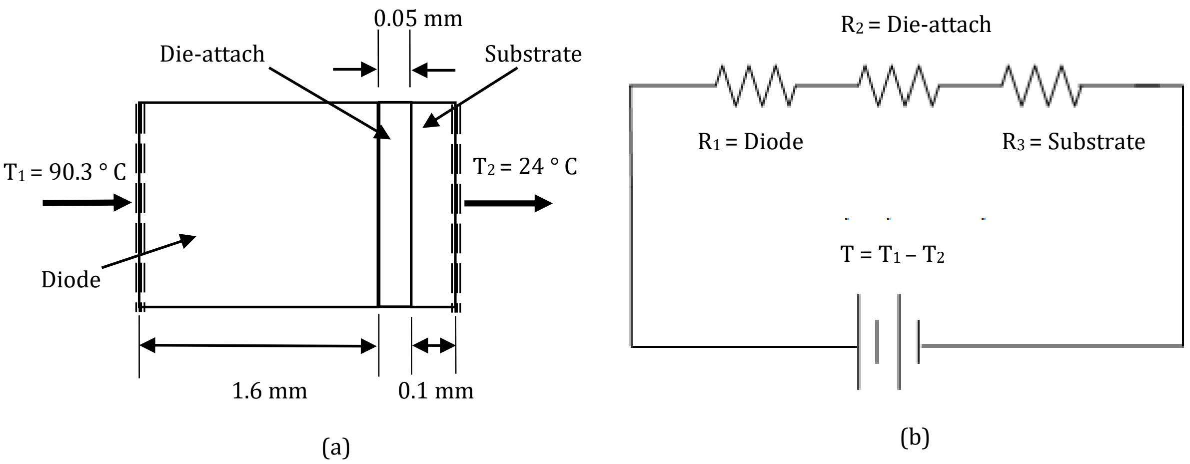


Figure 3. Schematic diagram of; (a) Heat flows in the circuit. (b) Heat conductance in series.

Table 1 demonstrates that, except for circuits that use epoxy die-attach material, all total heat flux values for each type of die-attach material are close to each other. This is because the thermal conductivity of epoxy is the lowest and very low when compared to other die-attach materials.

Table 1 Calculated Total Heat Flux of Die-Attach Materials Circuit

Material	**Calculated Total Heat Flux (W/m^2)**
Au/Sn (80/20) braze	23.481×10^6
Nanoscale silver	24.545×10^6
SAC alloy solder paste	23.491×10^6
Epo-Tek P1011 epoxy	6.485×10^6
Graphene	24.978×10^6
Copper	24.769×10^6

Table 2 shows the dependent and independent parameters chosen for this study. For each variation in independent parameters or combination of them, the obtained output results are four dependent parameters. This process can be repeated until all possible combinations are completed (single, double, and triple faults). The conductive inks were used as circuits to connect all the diodes that use die-attach as adhesive. The simulation processed the independent parameters to generate results with dependent parameters. The total heat flux used the dependent parameters to learn the heat flow of the conductivity of the conductive ink and obtained the independent parameters that are affected by it. Heat flow performance was obtained from calculations with imposed conductivity specified as independent parameters from Figure 1. In addition, structural parameters such as the adhesive thickness and material properties were also dependent parameters that had the effect of conductivity development with the aid of thermal analysis.

Table 2 Chosen Dependent and Independent Parameters

Dependent Parameters	**Independent Parameters**
Conductive inks outlet temperature	Conductive inks heat flow
SiC dies outlet temperature	Diode area
Die-attach thickness	Die-attach heat flow
Substrate temperature	Substrate area

2.4 Die-attach Properties

Die-attach materials are one of the most important aspects of microelectronics assembly. Die-attach materials or adhesives have more functions other than only to keep the die in place on the die pad, substrate, or hollow. They also offer thermal and/or electrical conductivity between the die and the package, consequently influencing the device's performance while in use. As a result, the selection of the best die-attach material for a semiconductor device and application is critical [13].

The first attempt to establish simulation baseline findings produced maximum temperatures ranging from 37.3 °C to 38.3 °C on SiC dies using metallic die-attach materials and a maximum temperature of 90.3 °C on the die with epoxy die-attach. It happens because epoxy has substantially lower thermal conductivity than metallic die-attach materials, it causes higher temperatures on the SiC diodes than metallic die-attach materials. Three of the four die-attach materials investigated were metallic and had high thermal conductivity. Epo-Tek P-1011 single-element polyimide epoxy was the fourth die-attach substance used. The material properties used for this FEA research are presented in Table 3.

Table 3 Material Properties Used for Simulation Analysis

Materials	Properties			
	Density (kg/m^3)	**Thermal conductivity (W/m °K)**	**Specific Heat (J/kg-K)**	**Reference**
Au/Sn (80/20) braze	14510	57	150	[13]
Nanoscale silver	8580	200	233	[13]
SAC alloy solder paste	7400	57.26	220	[13]
Epo-Tek P1011 epoxy	3190	1.29	628	[13]
Graphene	2200	5300	5.09×10^5	[1]
Copper	8300	401	385	[16]
SiC (Diode)	3215	120	650	[17]

According to [18], the thickness of the die-attach layer influences the heat conductivity of the die-attach. The thermal resistance of the material reduces as the thickness of the die-attach material decreases. The thermal resistance of a material is proportional to its thermal conductivity coefficient, heat transfer area, and thickness, as stated in Equation (4).

$$R_{Th} = \frac{\mathrm{L}}{\mathrm{kA}} \tag{4}$$

where R_{Th} represents thermal resistance, k and A represent thermal conductivity coefficient and heat transfer area, respectively, and L represents die-attach material thickness.

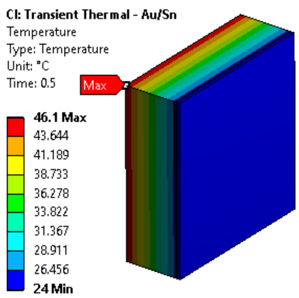
According to the researcher's findings [18], the thermal conductivity of the die-attach layer can reach 67 W/m.K, with k being the most influential factor. Thermal resistance obtained from the manual calculation based on Equation 4 can be utilized to validate the value of thermal conductivity derived from the simulation result for each die-attach material.

3. RESULTS AND DISCUSSION

3.1 Numerical Results

The modelling approach produced the best simulation results which accounted for the room temperature of the circuit at a constant 24 °C. Figures 4 and 5 show a surface plot of calculated surface temperatures and total heat flux, respectively on the model within 1.5 seconds of heating. Before commencing the discussion on mesh and time refinement of various die-attach models, it is pertinent to present heat flow inside the model within 1.5 s. The heat contour and the transient thermal on the conductive inks between 0.5 seconds and 1.5 seconds when using the TPC method in ANSYS are presented in Figures 4 and 5.

The transient thermal on the dies between 0.5 s, 1.0 s, and 1.5 s when using the TPC method in ANSYS is presented in Figures 4 and 5. From Figure 4 of the transient thermal data from 0 s to 1.5 s, the divergence occurs when the temperature spreads to the entire model and shows the reaction of the temperature color contour change on the circuit. On the diode surface, the temperature rises linearly from 0 to 1.5 seconds before flowing through the die-attach material to the substrate surface, which is 24 °C. Color contour is the same for all types of die-attach materials except for die-attach epoxy, as shown in Figure 4 at 0.5, 1.0, and 1.5 seconds. When compared to other die-attach materials, die-attach epoxy has the reddest areas. This indicates that epoxy does not have good heat conduction because heat is trapped and cannot easily flow through the die-attach material and substrate layers. The temperature spread at a high temperature to the substrate between 0.5 and 1.5 seconds. The heat gradually covers part of the area of the dies up to the substrate at 1.5 s until the temperature reaches a maximum value of 90.3 °C. These temperature loads observed in various time step sizes, mesh sizes, and simulation models are presented in this paper. The red area is only on the diode part at maximum temperature, and it begins to change color from red to blue on the die-attach part.



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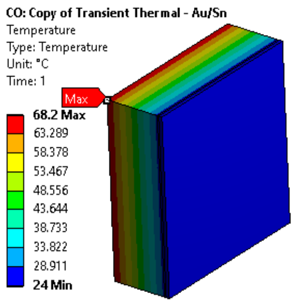

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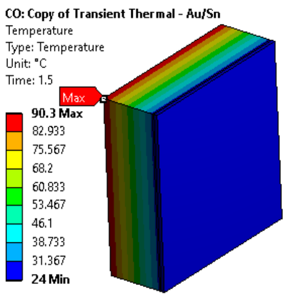

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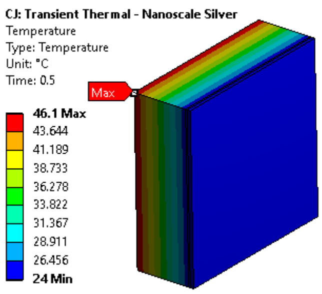

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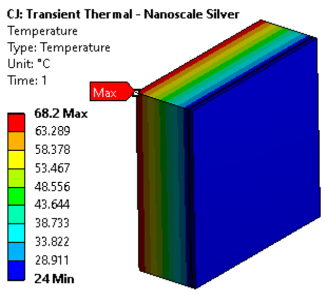

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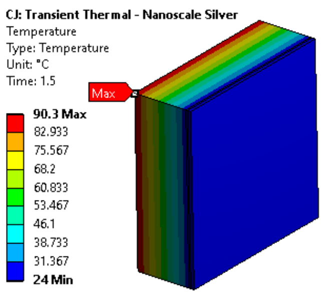

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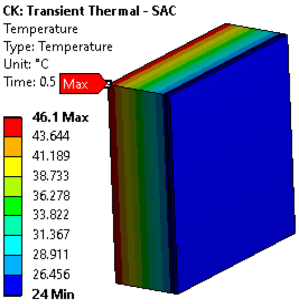

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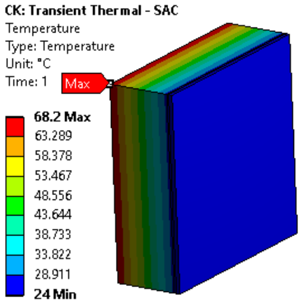

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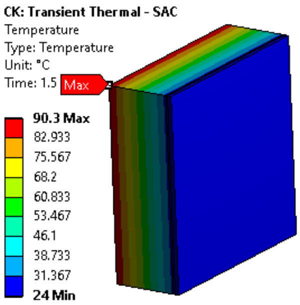

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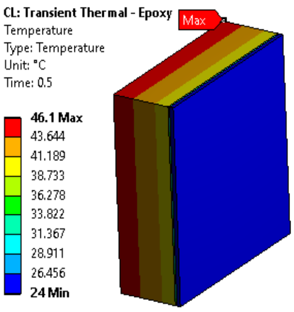

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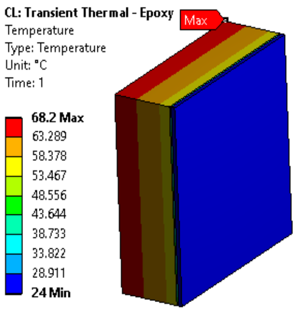

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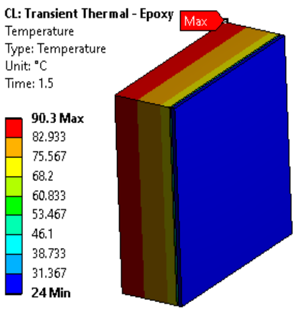

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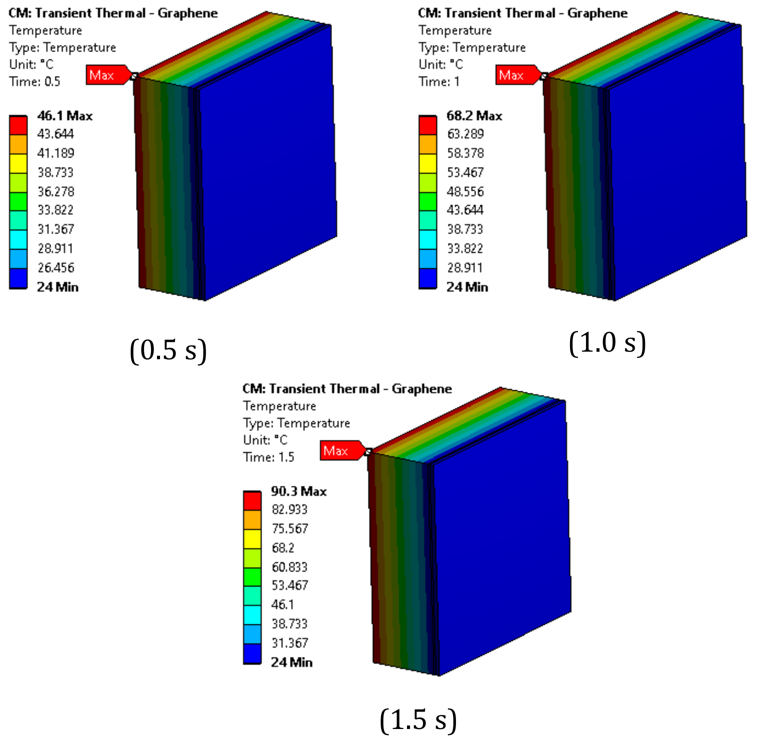

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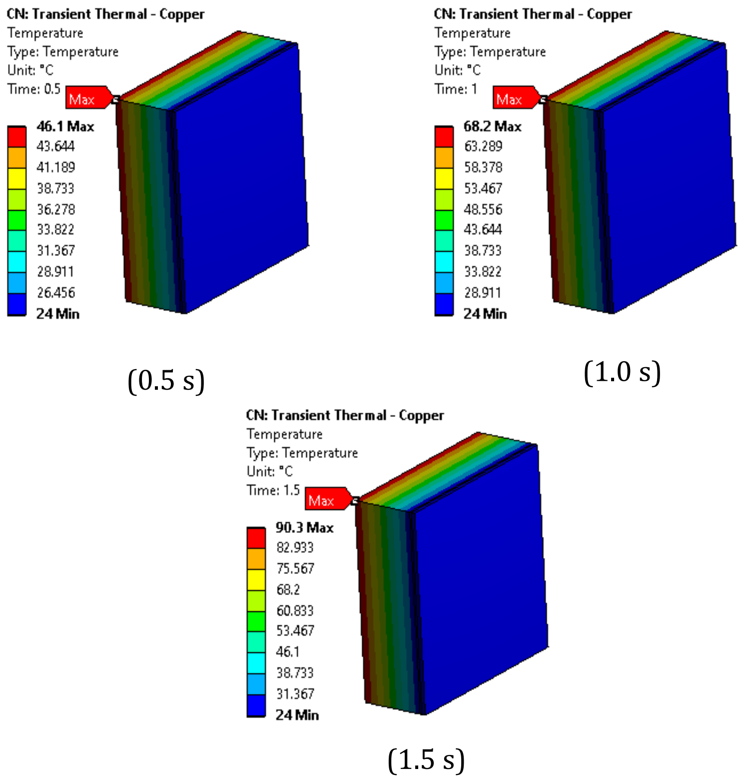
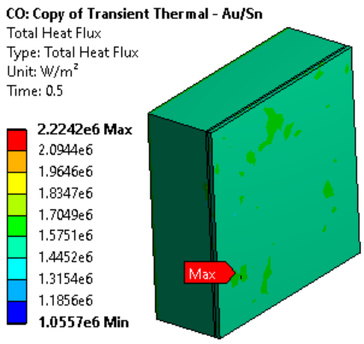


(f)

Figure 4. Temperature results of die-attach materials using transient thermal analysis. (a) Au/Sn (80/20) braze, (b) Nanoscale silver, (c) SAC alloy solder paste, (d) Epo-Tek P1011 epoxy, (e) Graphene and (f) Copper.

Total heat flux or heat flow rate intensity results as shown in Figure 5 is a flow of energy per unit of area per unit of time in the circuit. The heat flux becomes higher after the time and temperature are increased. The adaptive time-stepping method was implemented in all six die-attach materials models. The heat flows on the dies through die-attach materials to the substrate from 0 s to 1.5 s show a change in the color contour on the surface of the circuit model. Figures 5 (a), (b), (c), and (f) illustrate that the heat generated on the surface of the die from 0.5 to 1.5 seconds has little effect on the color contour of the model. This gives the impression that the model's state is unaffected by the increase of overall heat flux. The color contour appears to change in Figures 5 (d) and (e) as time and total heat flux increase. In Figure (d), die-attach epoxy changes from a yellowish color to a green color contour on a portion of the diode surface. Figure 5 (e) indicates that the blue areas are increasing in size while the green portions are shrinking. During the time changes from 0.5 s to 1.0 s and 1.0 s to 1.5 s, the heat conduction expands along with the conductive ink. All six simulation models were initiated with the maximum allowed time step size that can maintain the stability of the solving process. Therefore, the same time-stepping method was used in all the circuit models.



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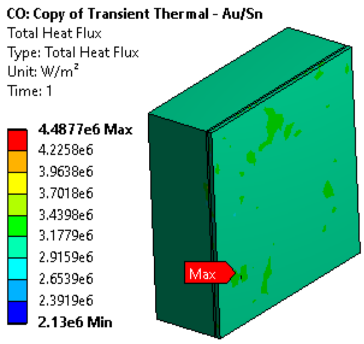

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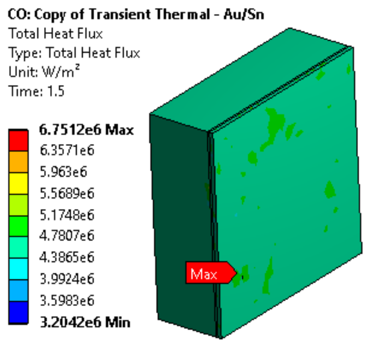

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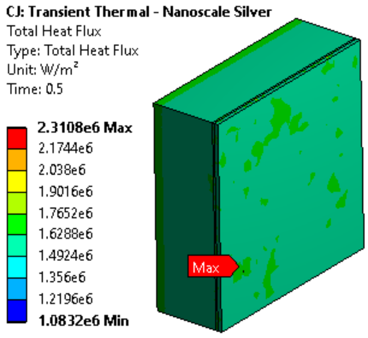

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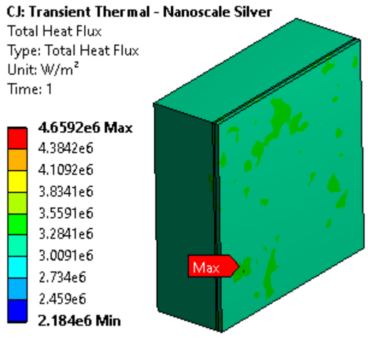

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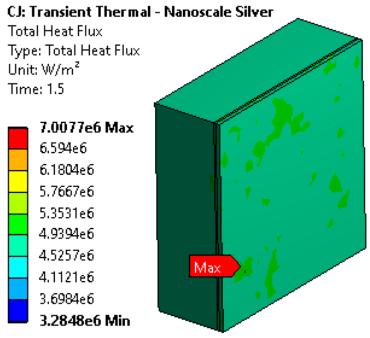

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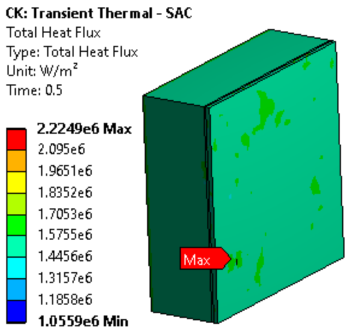

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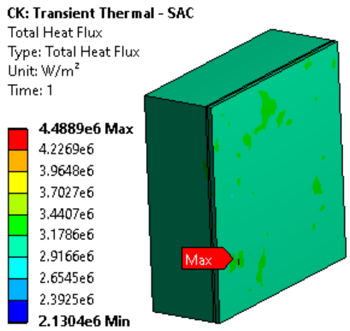

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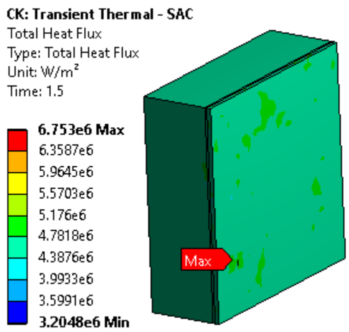

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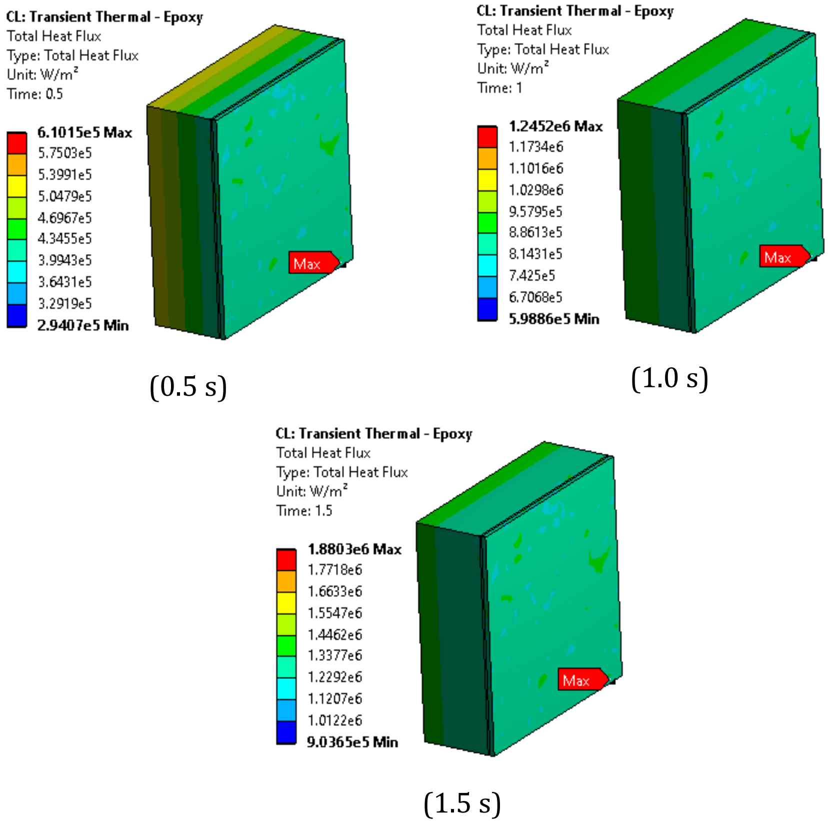
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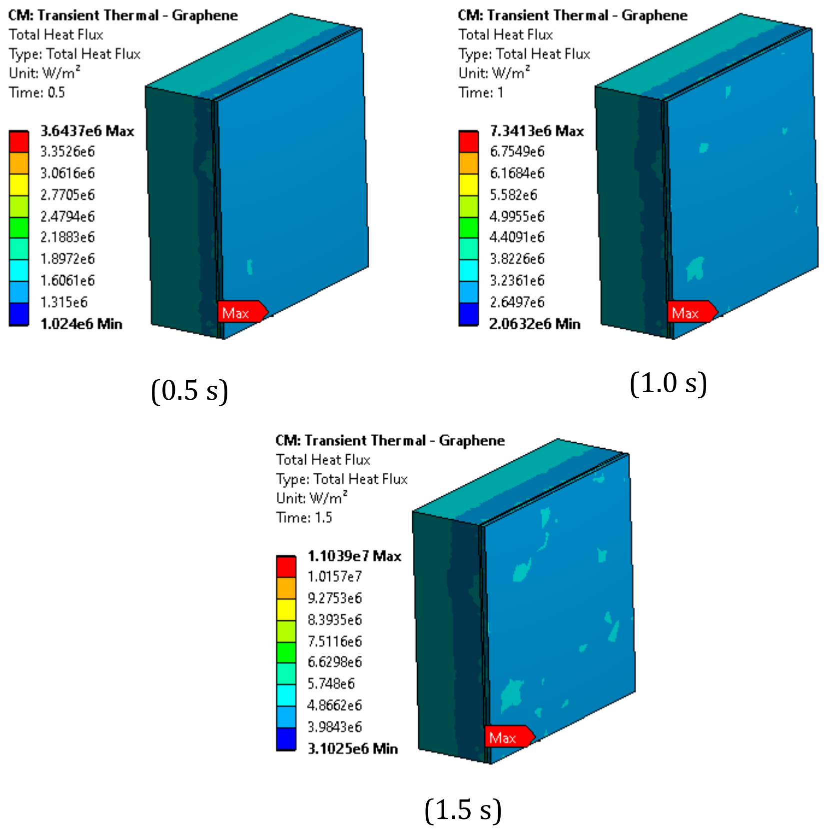
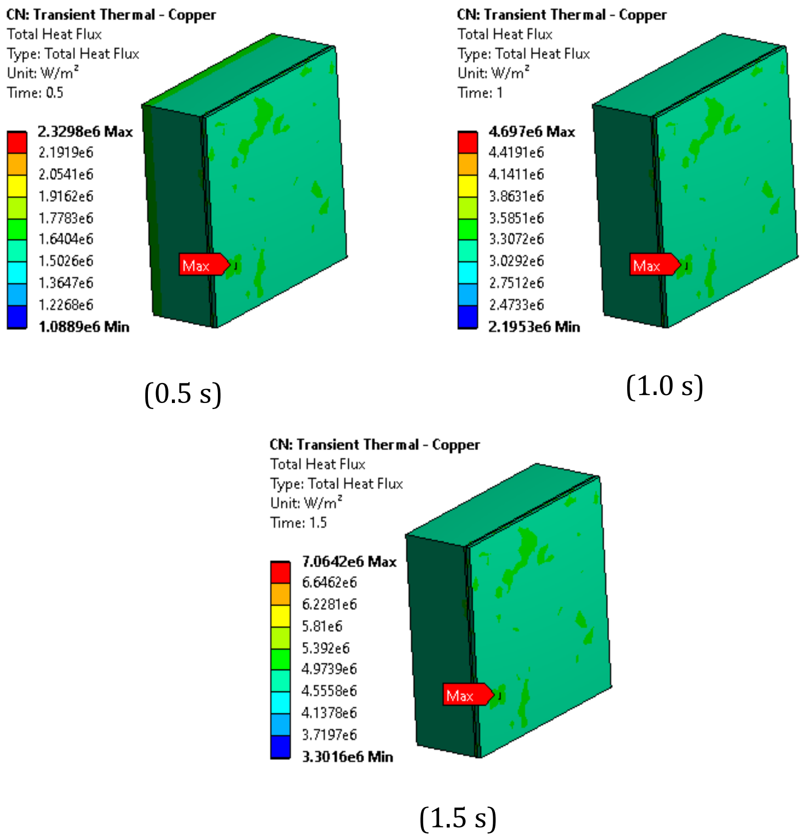
5.3991e5
5.0479e5
4.6967e5
4.3455e5
3.9943e5
3.6431e5
3.2919e5
2.9407e5 Min
Max
(0.5 s)
CL: Transient Thermal - Epoxy
Total Heat Flux
Type: Total Heat Flux
Unit: W/m²
Time: 1
1.2452e6 Max
1.1734e6
1.1016e6
1.0298e6
9.5795e5
8.8613e5
8.1431e5
7.425e5
6.7068e5
5.9886e5 Min
Max
(1.0 s)
CL: Transient Thermal - Epoxy
Total Heat Flux
Type: Total Heat Flux
Unit: W/m²
Time: 1.5
1.8803e6 Max
1.7718e6
1.6633e6
1.5547e6
1.4462e6
1.3377e6
1.2292e6
1.1207e6
1.0122e6
9.0365e5 Min
Max
(1.5 s)

(d)


CM: Transient Thermal - Graphene
Total Heat Flux
Type: Total Heat Flux
Unit: W/m²
Time: 0.5
3.6437e6 Max
3.3526e6
3.0616e6
2.7705e6
2.4794e6
2.1883e6
1.8972e6
1.6061e6
1.315e6
1.024e6 Min
Max
(0.5 s)
CM: Transient Thermal - Graphene
Total Heat Flux
Type: Total Heat Flux
Unit: W/m²
Time: 1
7.3413e6 Max
6.7549e6
6.1684e6
5.582e6
4.9955e6
4.4091e6
3.8226e6
3.2361e6
2.6497e6
2.0632e6 Min
Max
(1.0 s)
CM: Transient Thermal - Graphene
Total Heat Flux
Type: Total Heat Flux
Unit: W/m²
Time: 1.5
1.1039e7 Max
1.0157e7
9.2753e6
8.3935e6
7.5116e6
6.6298e6
5.748e6
4.8662e6
3.9843e6
3.1025e6 Min
Max
(1.5 s)

(e)



(f)

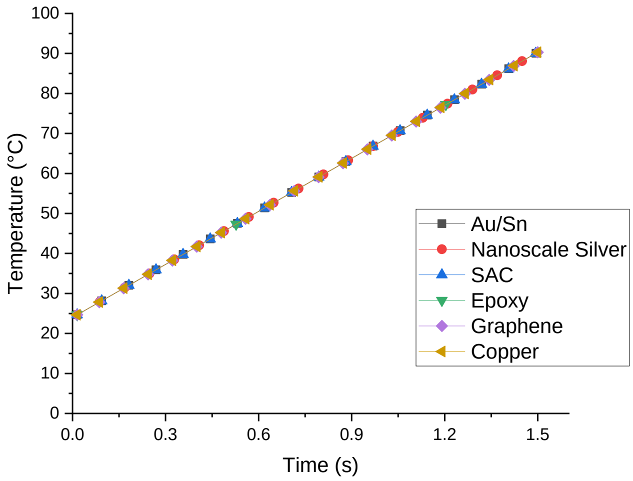
Figure 5. Total heat flux results of die-attach materials using transient thermal analysis.
(a) Au/Sn (80/20) braze, (b) Nanoscale silver, (c) SAC alloy solder paste, (d) Epo-Tek P1011 epoxy, (e) Graphene, and (f) Copper.

The results of the six die-attach materials showed little variation in values. The transient thermal simulation results summarized in Table 4 show that die-attach material, epoxy within time-dependent, 1.5 seconds has the lowest maximum total heat flux, with the value of 1.88 x 10^6 W/m^2. The finding is consistent with the findings of calculated total heat flux, in which epoxy has the lowest thermal conductivities among other die-attach materials.

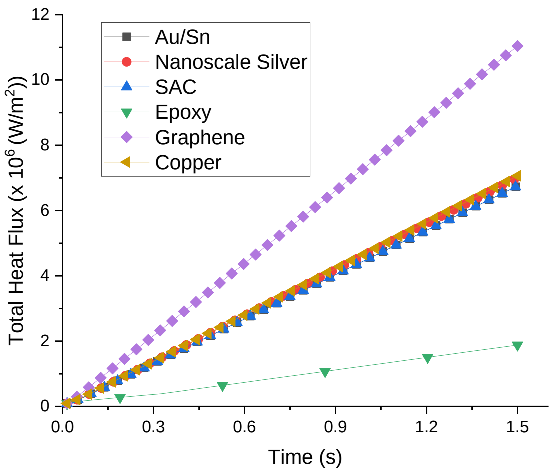
Even though epoxy has a lesser thermal conductivity than other die-attach, the high specific heat value has an effect on temperature conduction in the circuit [13]. Graphene has the highest results of total heat flux. This indicates that the heat transfer to the model on the graphene is decreased due to the temperature differential on the diode (SiC) as compared to the high thermal conductivity of the die-attach material. Nanoscale silver, copper, SAC alloy solder paste, and Au/Sn (80/20) braze are metallic die-attach materials with temperature and total heat flux results that are practically identical when applying graphene conductive inks.

Table 4 Transient Thermal Results of Die-Attach Materials Simulation

Time (s)	Die-attach											
	Au/Sn (80/20) Braze		Nanoscale Silver		SAC Alloy Solder Paste		Epo-Tek P1011 Epoxy		Graphene		Copper	
	Temp. (°C)	Total heat flux (W/m²)	Temp. (°C)	Total heat flux (W/m²)	Temp. (°C)	Total heat flux (W/m²)	Temp. (°C)	Total heat flux (W/m²)	Temp. (°C)	Total heat flux (W/m²)	Temp. (°C)	Total heat flux (W/m²)
0.5	46.1	2.224 x 10^6	46.1	2.311 x 10^6	46.1	2.225 x 10^6	46.1	0.61 x 10^6	46.1	3.644 x 10^6	46.1	2.33 x 10^6
1.0	68.2	4.488 x 10^6	68.2	4.659 x 10^6	68.2	4.489 x 10^6	68.2	1.245 x 10^6	68.2	7.341 x 10^6	68.2	4.697 x 10^6
1.5	90.3	6.751 x 10^6	90.3	7.008 x 10^6	90.3	6.753 x 10^6	90.3	1.88 x 10^6	90.3	11.04 x 10^6	90.3	7.064 x 10^6



(a)



(b)

Figure 6. Trend of the lines probes during the test, comparison between all four die-attach materials specimen. (a) Temperature with respect to time. (b) Total heat flux with respect to time.

This simulation result can be varied by comparing the calculated total heat flux in Table 1 with the heat flux simulation result, which shows negligible changes. Figure 6(a) shows the linear relationship between temperature and time rise during heating within 1.5 s over a temperature range of 24 to 90.3 °C. All die-attach material temperature results are increasing as time increases. The temperature has increased linearly since the first load is applied to the surface of the diode. The temperature and total heat flux have become increasingly spread over the entire models, especially in die-attach graphene, where the condition of maximum total heat flux is higher than other die-attach materials, as shown in Figures 5. A fitting line is established to determine a linear relationship with a temperature load of 90.3 °C.

Graph 6(b) depicts an increase in total heat flux for all die-attach materials during the first 1.5 seconds of heating. In comparison to other types of die-attach, the maximum total heat flux on the epoxy die-attach is the lowest. This demonstrates that epoxy provides high thermal resistance after measuring a temperature difference over a die-attach layer material with low thermal conductivity and 0.05 mm thickness. Because of the high thermal resistance, heat flows through the epoxy die-attach becomes more difficult. The graphs of Figure 6(a) reveal that all six die-attach materials are close to each other since the results produced from this transient thermal investigation are not significantly dissimilar. This is because the temperature applied to the diode surface is raised linearly from the beginning when the load is applied at 0 to 1.5 s.

The thinness of the die-attach materials layer has a little effect on the circuit's temperature and heat flux conduction, allowing heat to flow more easily. Except for nanoscale silver, copper, Au/Sn, and SAC die-attach, other die-attach materials show extremely large variances between metallic type die-attach and epoxy, as shown in Figure 6 (b). Metallic and carbon die-attach has a higher thermal conductivity than epoxy die-attach, which allows them to conduct temperature and heat more effectively. The thermal resistance decreases as the thickness of the die-attach material decreases. The thermal resistance of the material was only a small part of the total thermal resistance of the die-attach layer [18].

The thermal resistance of a material is proportional to its thermal conductivity coefficient, heat transfer area, and thickness, as given in Equation 1. This shows that a material's thickness has a significant impact on its temperature flow rate. Table 5 shows that the thermal resistance of all die-attach materials is too low and does not differ significantly. Because the size of the die-attach materials is too small and the thermal conductivity of the properties of the material is lower than other materials and semiconductor devices, the circuit temperature and total heat flux are not affected as much. This can be demonstrated by comparing the simulation's total heat flux values to the calculated total heat flux in Table 1. The high thermal conductivity of graphene conductive filler has a significant impact on other materials' overall thermal conductivity.

As shown in Table 5, the manual calculation of epoxy adhesive has the highest thermal resistance of all die-attach materials due to its low thermal conductivity value, which means that the temperature differential across the epoxy resists heat flow and heats the circuit for 1.5 seconds at a higher temperature than other adhesives. A small amount of heat is spreading across the circuit's face due to the use of high thermal resistance die-attach materials. If significant heat spreading occurs, the diode would have influenced the whole circuit and raised the maximum temperatures on the diodes.

Table 5 Thermal Resistance of Die-Attach Materials

Material	Thermal Resistance (°C/W)
Au/Sn (80/20) braze	9.746×10^{-2}
Nanoscale silver	2.778×10^{-2}
SAC alloy solder paste	9.702×10^{-2}
Epo-Tek P1011 epoxy	430.663×10^{-2}
Graphene	0.104×10^{-2}
Copper	1.385×10^{-2}

4. CONCLUSION

By using transient thermal analysis, the study was effective in proving the optimal heat conductivity performance of various die-attach materials. A modelling approach related to thermal theories was developed to investigate the varying effects of the different die-attach materials on the semiconductor device and substrate materials. Graphene produced the highest thermal value for die-attach materials in terms of maximum temperature and total heat flux. The FEA indicated that graphene, a carbon-based die-attach material, had the highest electrical and thermal conductivities than metals with the maximum total heat flux value of 11.04×10^6 W/m^2. Because of the low thermal conductivity, this transient thermal analysis found that epoxy die-attach material had the lowest total heat flux value of 1.88×10^6 W/m^2. All the results for four metal-based die-attach materials were close to each other which indicates the thermal conductivity and thickness had become the parameters with the greatest influence. Temperature and heat flux conduction to the circuit was unaffected by the thinness of the die-attach materials layer. As the thickness of the die-attach material decreased, the thermal resistance tended to fall. As a result, graphene die-attach materials with the best thermal resistance and highest thermal conductivity have the best potential to be good adhesives.

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