

Simulations and measurements of annealed pyrolytic graphite–metal composite baseplates

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Abstract. We investigated the usability of anisotropic materials as inserts in aluminum-matrix-composite baseplates for typical high performance power semiconductor modules using finite-element simulations and transient plane source measurements. For simulations, several physical modules can be used, which are suitable for different thermal boundary conditions. By comparing different modules and options of heat transfer we found non-isothermal simulations to be closest to reality for temperature distribution at the surface of the heat sink. We optimized the geometry of the graphite inserts for best heat dissipation and based on these results evaluated the thermal resistance of a typical power module using calculation time optimized steady-state simulations. Here we investigated the influence of thermal contact conductance (TCC) between metal matrix and inserts on the heat dissipation. We found improved heat dissipation compared to the plain metal baseplate for a TCC of 200 kW/m²/K and above. To verify the simulations we evaluated cast composite baseplates with two different insert geometries and measured their averaged lateral thermal conductivity using a transient plane source (HotDisk) technique at room temperature. For the composite baseplate we achieved local improvements in heat dissipation compared to the plain metal baseplate.

1. Introduction

A common method to improve heat dissipation in electronic devices is the usage of anisotropic materials [1–4]. These materials, like annealed pyrolytic graphite, have a very high thermal conductivity in two spatial directions and a low conductivity in the third direction [3]. Figure 1 shows an illustration of a typical power module. Most real life power modules, like figure (b), consist of several IGBTs (insulated-gate bipolar transistor) and FWDs (freewheeling diode) pairs connected to each other via wire bonds.



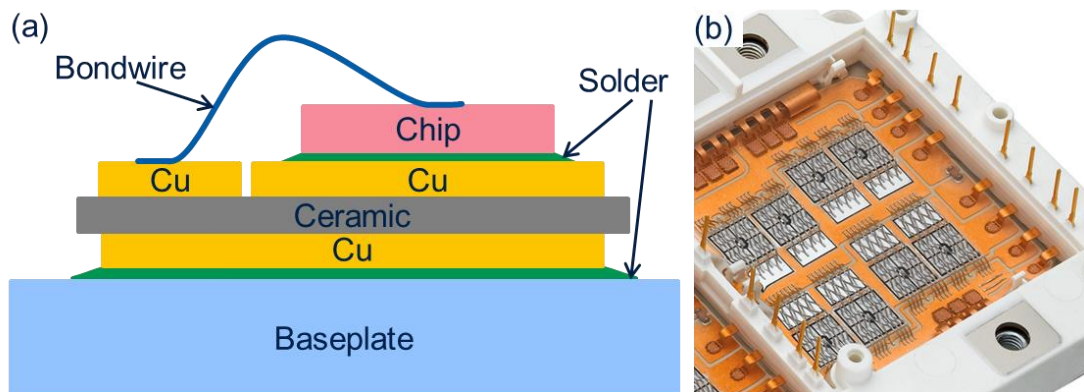


Figure 1. (a) Schematic illustration of a typical power module, (b) section of an Infineon HybridPack™ power module used for automotive applications.

The performance and lifetime of a power module strongly depend on its ability to dissipate the heat generated by the chips. The heat dissipation can be quantified by the thermal resistance R_{th} [K/W] of the package, which is inversely proportional to the thermal conductivity λ [W/m/K] of the materials used. One of the major obstacles for future generations of power modules are the increasing demands on system integration and power density. Both are accompanied by increased chip temperatures and hence decreased product lifetimes. The heat dissipation limit of conventional materials like Cu or Al is nearly reached. Hence for future devices novel materials with increased thermal conductivity need to be investigated. ‘Annealed pyrolytic graphite’ (APG) [5], a highly ordered graphite phase created by annealing turbostratic graphite is a possible candidate. APG has a thermal conductivity of above 1500 W/m/K in two spatial directions and 10 W/m/K in the third.

Aim of this work is to evaluate the usability of annealed pyrolytic graphite as inserts in metal matrices as a replacement for state-of-the-art plain metal baseplates for power modules.

3. Comparison of different simulation modules & insert geometries

Several physical modules (constant heat transfer ‘ht-const. h’, external forced heat sink ‘ht-efts’ and non-isothermal flow module ‘ntif’), suitable for different thermal boundary conditions, are investigated. By comparing three different physics modules and options of heat transfer we found non-isothermal simulations to be closest to reality for temperature distribution at the surface of the heat sink, but also the most time consuming. Reason is the modeling of an active flushing liquid heat sink. The benefit of this method is the calculation of the heat transfer coefficient at every single point of the heat sink surface instead of using a fixed heat transfer coefficient.

We optimized the arrangements of the graphite inserts in the metal matrix. Some examples of the results for insert optimization are given in figure 2. The result for simulation without APG shows the very low heat spreading. By arranging APG in-between the heat spots (APG 1) heat congestion occurs, the APG is not able to absorb and spread the heat efficiently. A better arrangement of APG-strips is the location directly underneath the heat spots. The thermal energy is transferred into the APG and is spread in the baseplate. The examples APG 2 and 3 show these kinds of arrangements with continuous and discontinuous stripes.

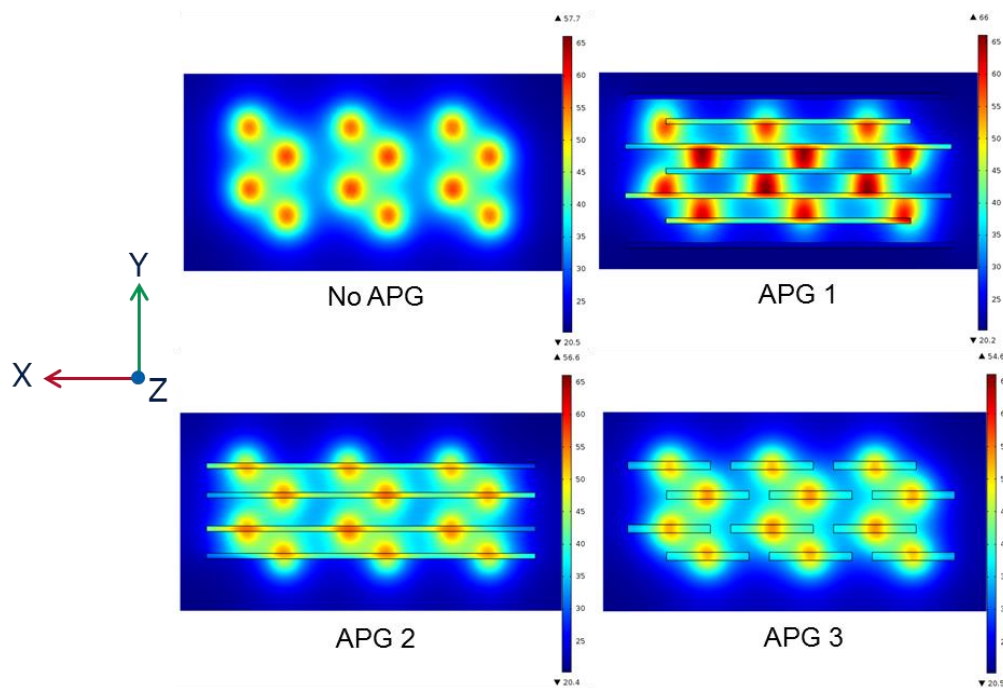


Figure 2. Selected results of temperature distribution at the heat sink surface (scale: 20 °C to 65 °C).

4. Influence of thermal contact conductance on heat dissipation

We evaluate the influence of the TCC between the Al matrix and the APG inserts on the heat dissipation of a power module using steady-state FEM simulations. We use a simplified structure of Infineon's HyridPack™1 power module as an example, allowing for general results applicable for most modules while still comparable to real-life products. In order to shift the simulation focus towards the baseplate and reduce calculation times we combine the thermal properties of the direct copper bonded substrate and both solder layers into one artificial substrate layer. The used model and the two different evaluated baseplate geometries are shown in figure 3. IGBTs are used as heat sources with an internal heat generation per volume resulting in 220 W per switch. A convection surface is attached to the bottom side; all other surfaces are perfectly isolated. The APG inserts are oriented with their high thermal conductivity in X and Z direction. All but the Al-APG interface have a perfect TCC.

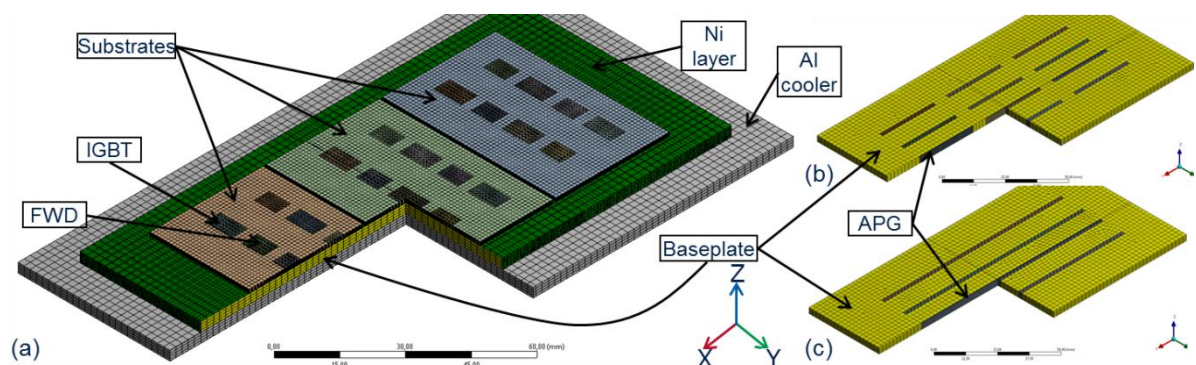


Figure 3. (a) Simulation model incl. mesh (scale: 60 mm); composite baseplate with 'short' (b) and 'long' (c) APG inserts (scale: 50 mm).

The maximum chip temperatures are calculated; the resulting temperature distributions and heat fluxes at the chip with the highest temperature are shown in figure 4. The highest calculated chip temperatures for both baseplate geometries depending on the TCC are given in table 1. Using a plain Al baseplate we calculate the maximum chip temperature to 133.8 °C. Compared to a plain Al baseplate the composite baseplate shows improved heat dissipation for a TCC as low as 200 kW/m²/K. For all TCCs the ‘long’ baseplate type performs better than the ‘short’ type. The inferior heat dissipation of the ‘short’ type can be explained with its reduced amount of APG and its interruptions within the APG inserts. This shows that heat dissipation in Z direction is not the only influencing factor. The continuous inserts allow for improved heat spreading in X direction and hence result in lower chip temperatures. The maximum chip temperature using a perfect thermal contact (infinite TCC) is more than 14 °C lower than that using a TCC of 10 kW/m²/K. This shows that the TCC has a major influence on the heat dissipation of module: if the TCC is too high the inserts act like pores and are detrimental to the heat dissipation.

Table 1. Maximum chip temperatures for both baseplate geometries depending on the thermal contact conductance between matrix and inserts. An infinite TCC represents perfect thermal contact.

TCC	[kW/(m ² K)]	∞	800	400	200	100	10
Max. chip temperature [°C]	‘short’	128.1	129.5	130.5	132.5	135.3	142.4
	‘long’	127.6	128.9	129.8	131.6	134.3	141.8

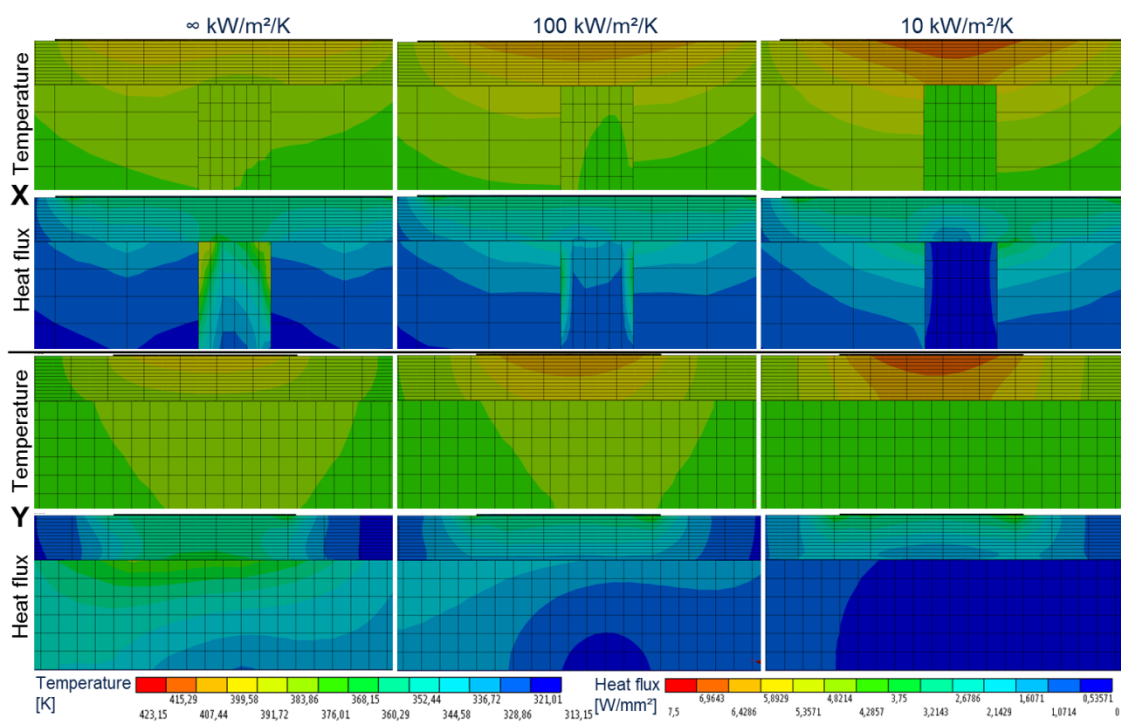


Figure 4. Simulation results using baseplate with ‘long’ inserts, cross-sections at chip with highest temperature. Temperature in row 1&3, heat flux in row 2&4. Viewing direction: rows 1&2 in X, rows 3&4 in Y direction. 1st column perfect TCC, 2nd column 100 kW/m²/K, 3rd column 10 kW/m²/K.

5. Measurement of cast composite baseplates

The lateral thermal conductivity of casted Al-alloy composite baseplates was investigated using a transient plane source technique (Hot Disk TPS 3500 by Hot Disk AB, Sweden, [6,7], sensor diameter 12.8 mm). We evaluated different sensor positions to investigate the influence of the TCC and the APG inserts on the heat dissipation as illustrated in figure 5. On the backside of the composite baseplates (the side the DCB would be soldered onto, not visible in figure 5) the inserts are not showing, instead a thin Al layer is between sensor and APG. For these backside measurements the sensor is positioned in X&Y direction just like the ‘in-between’ position on the front side. The average conductivities and standard deviations of the measurements are given in table 2. Measurements at the centered position show a higher conductivity than the position in-between the inserts, demonstrating that heat spreading in X direction occurs. The heat is dissipated anisotropically within the lateral dimensions beyond the marked areas in figure 5. Comparing the plain Al measurement with the Al-backside measurement reveals the detrimental effect of the TCC between Al and APG: Apparently the TCC is too low to allow heat absorption and dissipation by the inserts. Instead the inserts act like air pores and reduce the effective thermal conductivity. However if a heat source is positioned on top of an insert the effective thermal conductivity is improved significantly (more than 30%) compared to a plain Al baseplate.

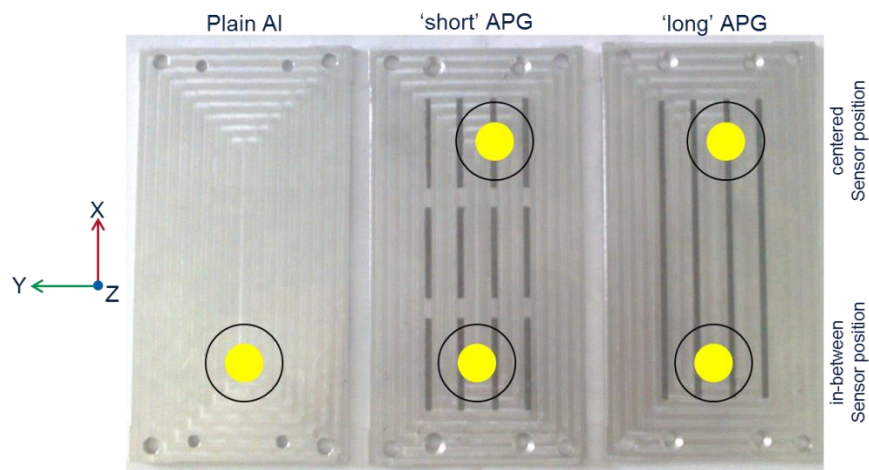


Figure 5. Image of the three different measured baseplate types. The yellow dots indicate the sensor position for the thermal conductivity measurements; the circle marks the maximum penetration depth for isotropic materials for the chosen measurement parameters based on the properties of the used Al-alloy.

Table 2. Lateral thermal conductivities for different sensor positions and baseplate types as illustrated in figure 5.

λ [W/(m K)]	Plain Al	‘short’ APG	‘long’ APG
Centered	N/A	162.2±0.7	153.8±2.0
In-between	122.3±1.1	113.5±1.6	98.0±0.7
Al-Backside	N/A	98.5±2.2	78.6±0.3

6. Summary and Outlook

Overall the performed simulations show that APG inserts in metal matrices can be used to improve the heat dissipation of high performance power semiconductor modules compared to plain Al alloy baseplates, if the insert arrangement in respect to the heat sources and their thermal contact conductance to the metal is optimized. These simulations have been confirmed by transient plane source measurements. During operation the baseplate of a power module bends due to thermal expansion. It is unclear whether the APG inserts break during the cyclic loads due to their brittle behavior. Hence in the next step we will evaluate the thermal conductivity of the cast composite baseplates after thermal cycling tests and create and evaluate a demonstrator power module.

Acknowledgments

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