The module without a baseplate: A reliable and cost-effective solution

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Abstract

Power modules serve a wide and diverse range of purposes. For some applications, power density is a key factor. For others, efficiency or price may be the sticking point. But for all applications, reliability is a top priority. This paper describes the differences between modules with and without baseplates, and how the reliability and thermal conductivity is affected.

Introduction

Modules with solid baseplates made of copper or aluminum silicon carbide are commonplace. Cost concerns have also given rise to a new breed of module without a baseplate. Figure 1 shows a *flow* 0 module without and a *flow* 2 module with a baseplate.

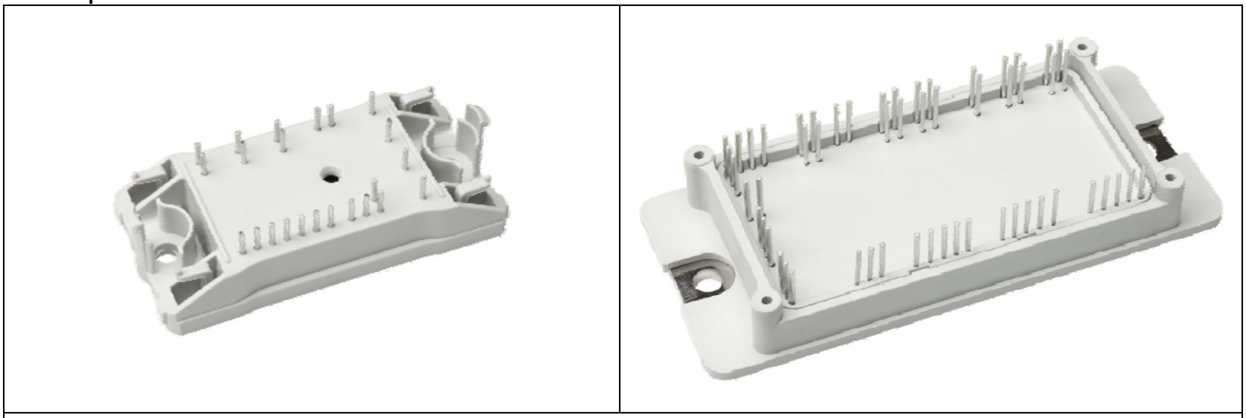


Figure 1: flow 0 DBC without and flow 2 with a copper baseplate

Pictured on the left is a module with direct bonded copper, or DBC for short.

State of the art

DBC substrates have proven their merits in power electronic applications over many years. The advantages of DBC substrates are many: They can handle high temperatures and current. Their coefficient of thermal expansion, or CTE, is a good match for that of silicon. They isolate high voltages and show low capacitance between the front and back sides.

When several aluminum oxide DBC substrates are used, they are often soldered to an additional baseplate. For some large modules equipped with a rectifier, brake, and an inverter, the rectifier and brake are soldered to one substrate, and the inverter IGBTs and freewheeling diodes to another.

AlSiC baseplates are often used for traction applications in place of copper plates. The materials have very different physical properties, with the CTE and thermal resistance being the key factors.

Thermal conductivity

Thermal conductivity describes a material's ability to conduct heat. It is measured in watts per meter Kelvin [W/mK].

A material must conduct heat well to help keep the average temperature of the die low. Also, temperature ripple is influenced by the conductivity of the material. Figure 2 shows a cross-section of DBC and baseplate modules without the housings and soft gel.

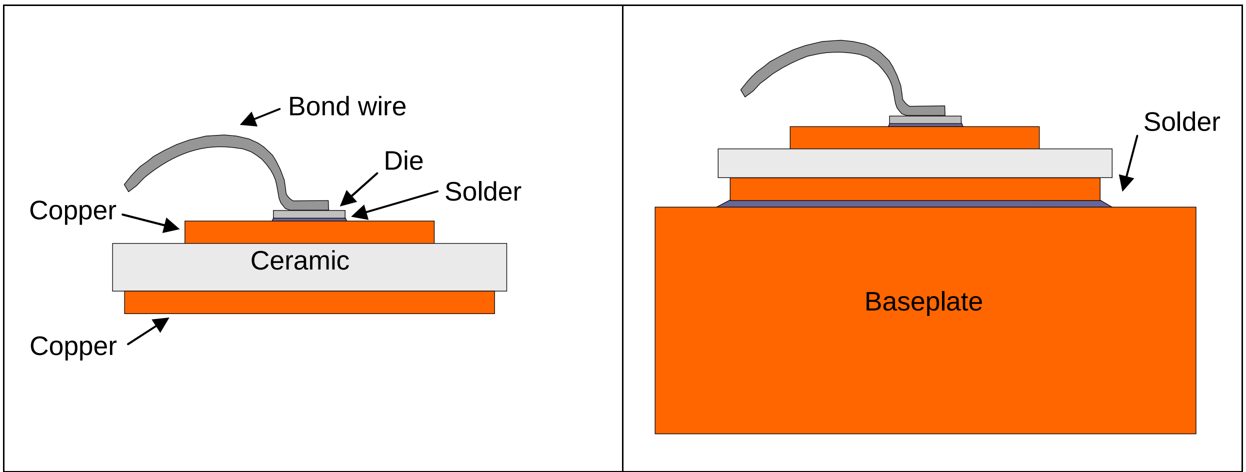


Figure 2: Cross-section of DBC and a baseplate module

These materials' thermal resistances differ, which explains why the temperature drop from the die to the case is nonlinear. Conductivities range from about 20 W/mK and 400 W/mK as shown in table 1 below.

Part	DBC module		Baseplate modules	
Die [W/mK]	Silicon [148]		Silicon [148]	
Solder [W/mK]	SnAg [62]		SnAg [62]	
DBC [W/mK]	Al_2O_3 [25]	AlN [155]	Al_2O_3 [25]	AlN [155]
Solder [W/mK]			SnAg [62]	
Baseplate [W/mK]			Cu [401]	AlSiC [180]

Table 1: Thermal resistance of module materials @ 25 °C

Cleary, DBC modules with an AlN ceramic conduct heat much more effectively, so the heat transfer from the top to the bottom is far better. What's more, a comparison of modules shows that copper baseplates' thermal resistance is lower than that of AlSiC baseplates. It follows that a material with higher thermal conductivity helps decrease the dies' junction temperature.

The coefficient of thermal expansion

The section above described the thermal conductivities of materials commonly used in power modules. The CTE is also critical to a power module's reliability. Thermal expansion is the tendency of a material's volume to change in response to temperature change. The CTE for all materials described below is measured in $[10^{-6}/K]$. Copper, for example, has a higher CTE than silicon. Given the same temperature increase for both materials, copper expands about six times more than silicon. Table 2 below shows key materials used in power modules.

Part	DBC module		Baseplate modules	
Die [10^{-6}/K]	Silicon [2.8]		Silicon [2.8]	
Solder [10^{-6}/K]	SnAg [22.1]		SnAg [22.1]	
DBC [10^{-6}/K]	Al_2O_3 [8.2]	AlN [4.5]	Al_2O_3 [8.2]	AlN [4.5]
Solder [10^{-6}/K]			SnAg [22.1]	
Baseplate [10^{-6}/K]			Cu [16.5]	AlSiC [8.4]

Table 2: The CTE of module materials @ 25 °C

This paper does not discuss the values for soft gel, the housing, and bond wires. Note that bond wires' CTE has an impact on the module's life time.

The CTE of Al_2O_3 is closer to silicon than copper. The CTE of AlN is also closer to that of Si, which reduces stresses in die attach materials. However, the stresses are actually higher in the joint between the copper baseplate and DBC because of the greater difference between the net CTE of the Al_2O_3 DBC and of the Cu baseplate. This causes the power module to bend further.

Typical substrate and baseplate materials' CTE may be several times that of silicon and other semiconductors'. This difference causes thermal stresses in the devices, solder interconnections, and substrates because the mismatches are frozen during the assembly process of the module at high temperatures, especially during the soldering process. These stresses can cause mechanical and fatigue failure, or changes in operating behavior. Mismatched CTE is not the only source of thermal stress in the device. The shear strength and stiffness of the joint material and the joint area are also factors. In IGBT power modules, the joint between the DBC and baseplate is much larger than the joint between the semiconductor and DBC, so it is more prone to failure brought on by thermal cycling. Consequently, the DBC may delaminate from the baseplate, which can cause thermal resistance to increase, temperature to rise, and cracks propagation. Finally, a module's compromised ability to remove heat may culminate in thermal runaway. Residual thermal stresses in the DBC-baseplate stack can also cause a bimetallic effect that bows the module. The deformation is concave because the copper baseplate's CTE is greater than that of the DBC. This creates a gap between the module and the heatsink, which increases this interface's thermal resistance even after thermal grease is applied. The bimetallic effect is proportional to temperature. The grease may be squeezed out if a thermal compound is applied and the module is mounted to a heatsink. This effect is knowen as the pump-out effect. Pre-bent, convex baseplates such as those used in *flow* 2 modules can compensate for this packaging-induced phenomenon.

Wear-out failures

Different wear-out failures are observable. But only the failures due to CTE or in other words mismatches of the stack are taken into account. This means that this failure can occur between every material with different temperature expansion coefficients.

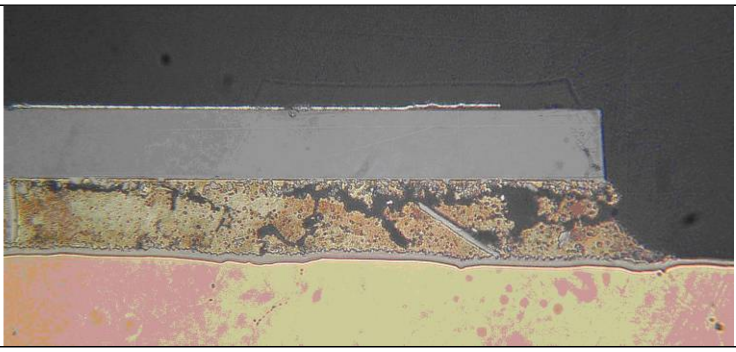


Figure 3: A delaminated solder layer

Delamination starts at the edges of the solder joint and expands inward. A larger joint is exposed to greater tensile forces, so small chips and solder joints are less likely to delaminate. One good way to tackle this problem is to assemble two small semiconductors rather than one large chip. This requires a bit more space but reduces wear-out failure and thermal resistance.

The same goes for soldering DBC substrates to baseplates. The solder layers for smaller DBC substrates are less susceptible to delamination. Both failures cause junction temperatures to rise and shorten the module's life.

Power modules' reliability also depends on the load profile. An uninterruptible power supply furnishes a constant load so the average junction temperature remains very stable. Also, a UPS works at 50 or 60 Hz so the die's ripple temperature remains low. All materials only see one cycle when the application powers up. After a few minutes, the entire application will run at a constant temperature. This is the best-case scenario for all components. In other applications such as welding, the power is switched on and off repeatedly. The devices generate losses that heat up the system, which cools down again while the power is switched off. This exposes components to many temperature cycles, which causes solder layers to delaminate.

There are several ways to counteract this effect. Smaller chips may be paralleled as described above, or the module may be oversized so that it generates less loss and therefore less heat. An efficient way of solving the problem is to use a module whose materials' CTE are well matched.

The reliability of different approaches
Again, reliability is a function of CTE values and the number of temperature cycles. To gain a better understanding of this we need to look closer at thermal spreading as shown in Figure 4.

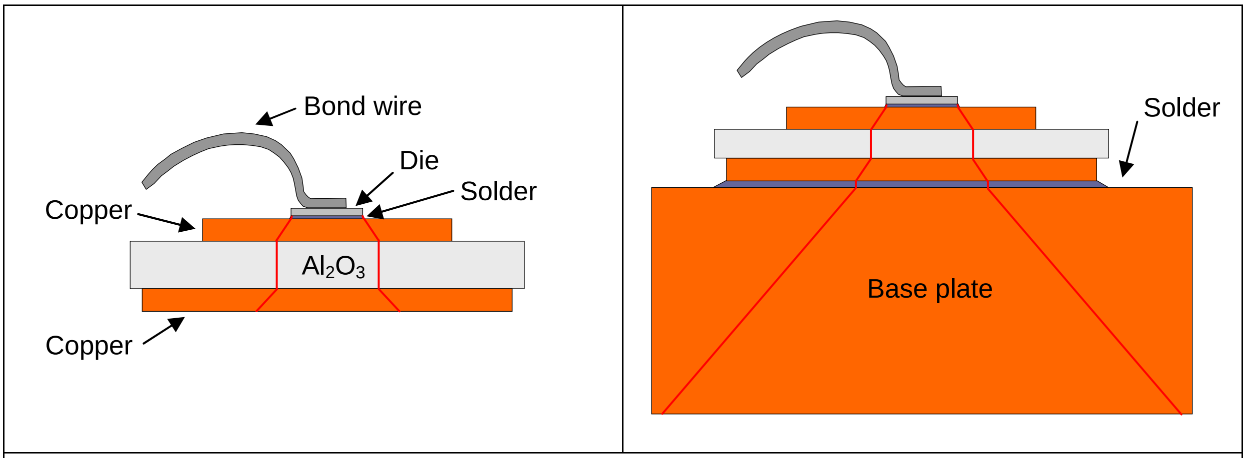


Figure 4: Thermal spreading of DBC and baseplate module

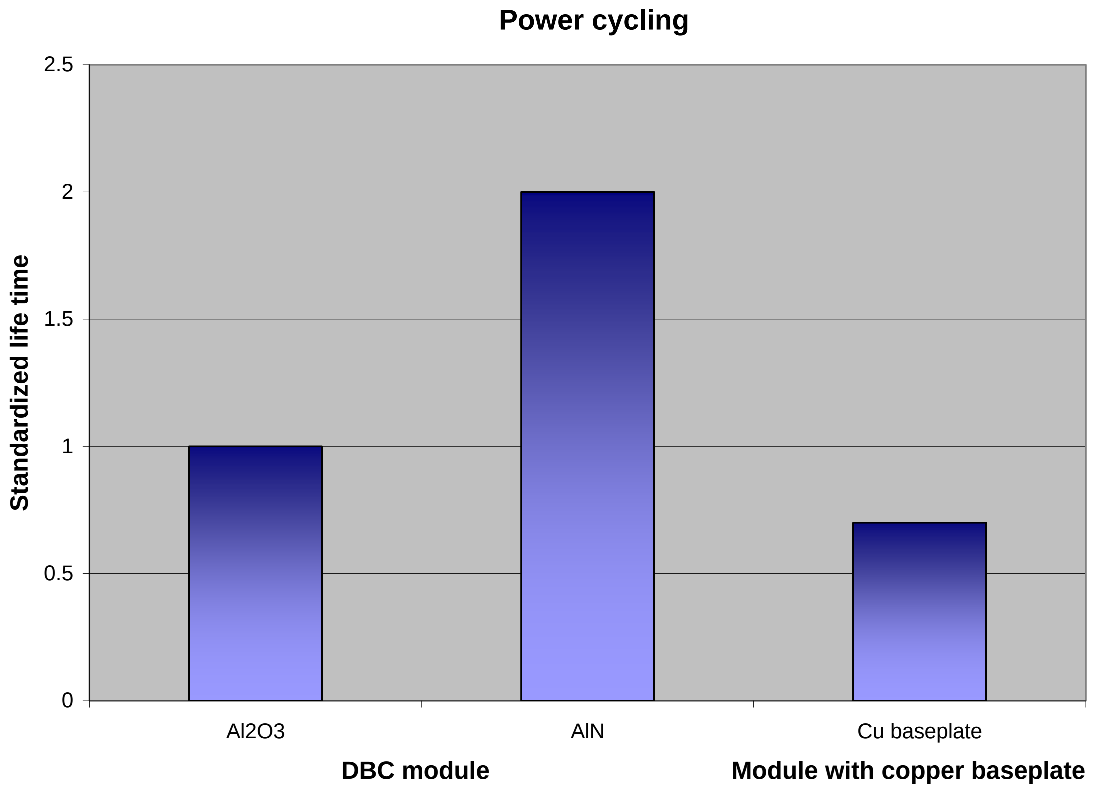
The red lines represent thermal spreading. It is obvious that the thermal spreading in each case depends on the next layer below.

Vincotech subjects each module to battery of quality and reliability tests during the qualification process. Two different tests assess the various materials' thermal expansion properties.

One is the load or power cycling test. It places considerable stress on the connection between the bond wire and semiconductor, generating substantial losses and a temperature drop from the semiconductor to the module's case.

The other test is the thermal shock test where the module is moved from a cold to a hot chamber for a certain time within a transition time of less than 30 seconds.

The chart below shows reliability data standardized to a DBC module equipped with an Al_2O_3 DBC. Test conditions for all three modules were equal. Chip size and number of chips were also identical. The temperature difference of each cycle was 100 K, starting from 25 °C to 125 °C.



The failure criterion was a 20% increase of $R_{th(j\text{-}c)}$ due to delamination.

This description of the CTE phenomenon and how it relates to reliability would not be complete without mentioning heat-driven expansion. The solder joint must absorb the silicon, DBC, and baseplate's expansions without failing. The challenge is to design a solder joint thin enough to ensure a low drop in temperature, yet thick enough to absorb the movement of joint materials. The temperature drop from top to bottom also has to be taken into account. The highest temperature is at the top where the die resides and lowest at the bottom where the heatsink sits.

The influence of thermal spreading

Again, each downward layer influences thermal spreading. The R_{th} values stated in Vincotech's datasheets are measured with a water-cooled heatsink. It absorbs energy very well, so very little thermal spreading occurs. The figure below illustrates thermal spreading in a water-cooled heatsink and in a conventional heatsink.

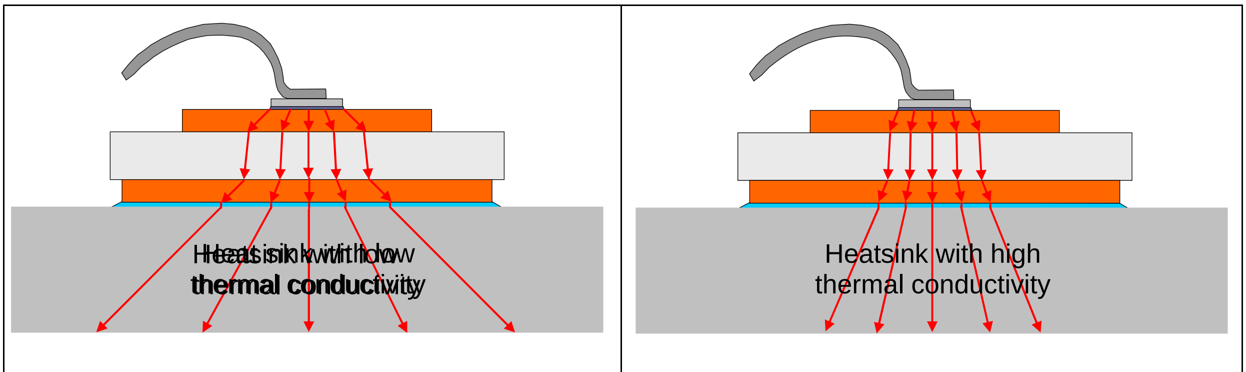


Figure 5: Thermal spreading with low- and high-conductivity heatsinks

The specifications for all modules are given for a water-cooled heatsink. This means the R_{th} values in the datasheets are worst-case values. If an air-cooled heatsink is used instead, thermal spreading is higher, which results in a better $R_{th(j-h)}$ value. The heatsink is not the only component to influence thermal spreading; the given thermal compound is also a contributing factor.

Conclusion:
Having examined different variants of modules, we can draw the following conclusions: The longest component life may be achieved by keeping temperature ripple low. The load and environmental conditions are key factors. The smaller the number and the lesser the extent of thermal expansions, the greater the reliability. The CTE of materials should match. If thermal capacity is not an issue, a module without a copper baseplate is the right choice.

Modules with baseplates may be necessary if brief spikes of high energy are expected. Each downward layer of material layer influences thermal spreading. R_{th} values stated in the datasheet are measured with a water-cooled heatsink and indicate the worst-case scenarios.