Reliable and Cost Effective Solution without Baseplate

Power modules are used for a wide range of different applications. For some applications the power density, the efficiency or the price is one of the key factors. But for all of them reliability is the major factor. This article describes the difference between modules with and without a baseplate and how reliability and thermal conductivity is affected. **Patrick Baginski, Field Application Engineer, Vincotech, Unterhaching, Germany**

Massive baseplates were used for power modules in the past. These can be made of Copper or Aluminum Silicon Carbide (AlSiC). Nowadays where costs play an important role, also modules without an additional baseplate can be found. Figure 1 shows a *flow* 0 module without and a *flow* 2 module with baseplate. Here, for the left picture, just the direct bonded copper (DBC) is mounted with a thermal interface material to a heatsink.

State of the art

DBC substrates have been proven for many years in power electronic applications. The advantages of DBC substrates are high thermal performance, Silicon matched coefficient of thermal expansion (CTE), high current capability, high voltage isolation and low capacitance between front and backside.

Aluminum Oxide (Al_2O_3) DBCs are often soldered to an additional baseplate when using more than one DBC. For some bigger modules with a rectifier, brake and an inverter part the first two mentioned parts are soldered to one substrate and the inverter IGBTs and freewheeling diodes to another substrate.

AlSiC baseplates are often used for tractions applications where plates made out of copper usually find place into power modules for all other applications. The differences of both materials that belong to modules are the physics. Especially the CTE and the thermal resistance are of interest.

Thermal conductivity

Thermal conductivity is the property of a material describing its ability to conduct heat. It is measured in watts per meter-kelvin [W/mK]. A high thermal conductivity is necessary to keep the average temperature of the die low. Also the temperature ripple is influenced by the conductivity of the material. Figure 2 shows a cross section of DBC and baseplate modules without housing and also without soft gel.

These materials have different thermal resistances. Therefore the temperature drop from the die to the case is not linear. Conductivities are between approximate 20 W/mK and 400 W/mK as shown in Table 1.

Clearly, 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 the copper baseplate's thermal resistance is lower than that of AlSiC baseplates. It follows that a material with higher thermal conductivity helps decrease the die's junction temperature.

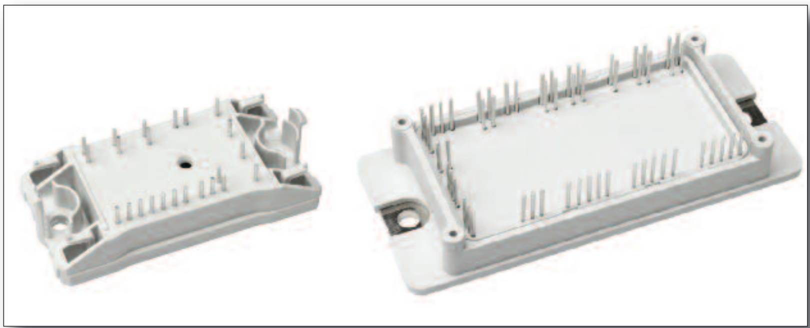

Figure 1: **DBC based *flow* 0 power module (left) and *flow* 2 with copper baseplate**

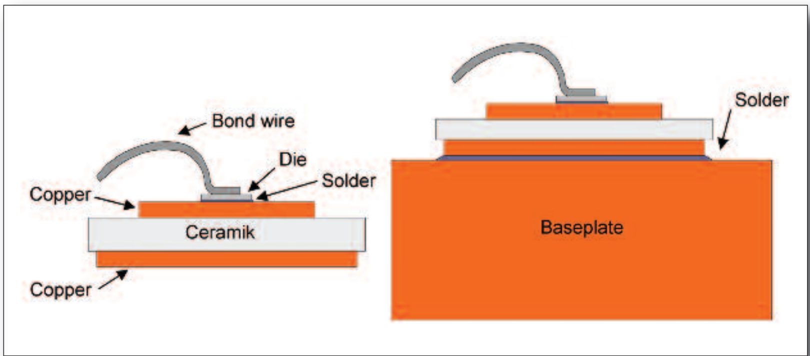

Figure 2: **Cross section of DBC and baseplate module**

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 shows key materials used in power modules.

Values of soft gel, housing and also bond wires are not discussed here. It should be mentioned only that also the CTE of the bond wires makes a contribution to the life time of modules.

The CTE of Al_2O_3 for example is closer to the Silicon compared to copper. Although the CTE of AlN is closer to that of Si, which reduces stresses in die attach materials,

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]	AlN [155]	
Solder [W/mK]			SnAg [62]	
Baseplate [W/mK]			Cu [401]	AlSiC [180]

Table 1: **Thermal resistance of module materials at 25°C**

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]	AlN [4.5]	
Solder [10^{-6}/K]			SnAg [22.1]	
Baseplate [10^{-6}/K]			Cu [16.5]	AlSiC [8.4]

Table 2: **CTE of module materials at 25°C**

the stresses are actually higher in the joint between the copper baseplate and DBC. This is due to the increased CTE difference between the net CTE of the AlN DBC and Cu baseplate, which leads to a larger bending of the power module.

Typical substrate and baseplate material's 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 crack 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 is known 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.

Delamination starts from the edges of the solder joint and works to the middle of it (Figure 3). This is because of the absolute movement of the materials. Small chips and small solder joints do not have that high delamination compared to big solder joints. A good solution could be to assemble two small semiconductors instead of one big. This needs a bit more space but reduces the wear-out failure as well as the thermal resistance. The same method can be considered when it is necessary to solder DBCs to baseplates. Also here smaller DBCs helps to decrease the delamination of solder layers. Both failures cause an increase of junction temperature and reduce the lifetime of the module.

Power modules' reliability also depends on the load profile. An uninterruptible power supply (UPS) 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.

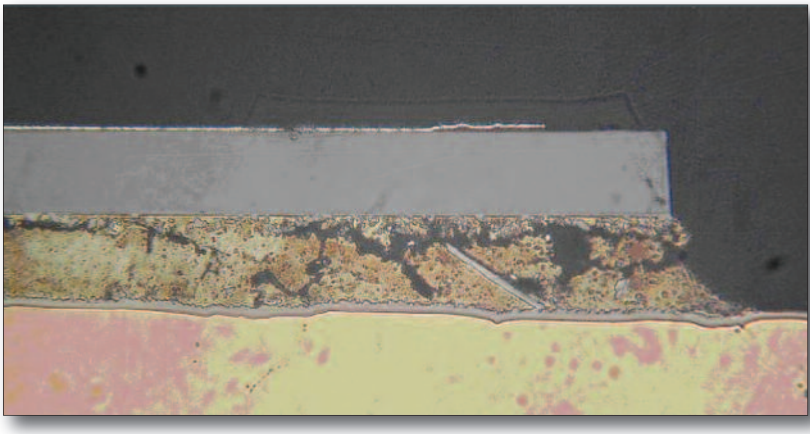

Figure 3: **Delamination of solder layer**

Reliability of different concepts

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.

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

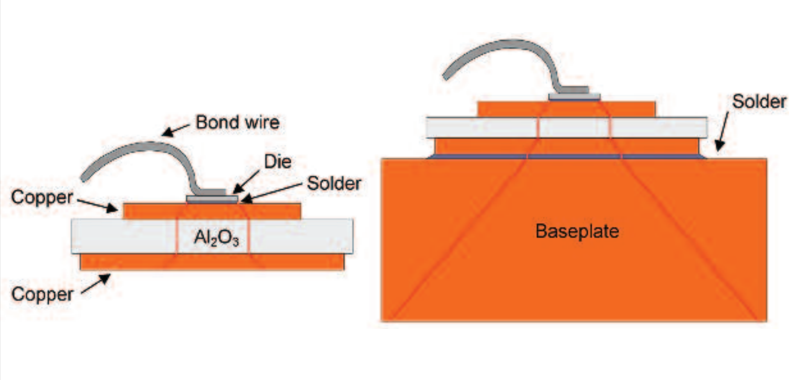

Figure 4: **Thermal spreading of DBC (left) and baseplate module**

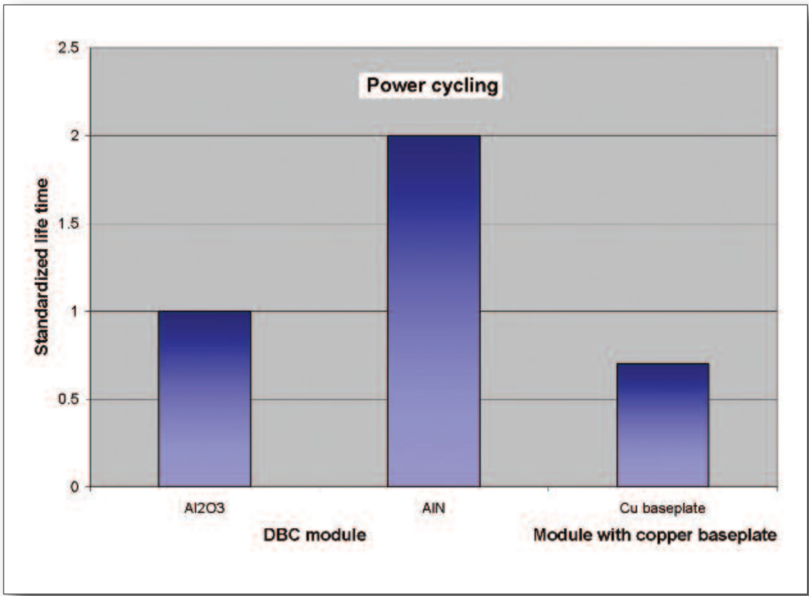

Figure 5: **Reliability data standardized to a DBC module with Al2O3 DBC**

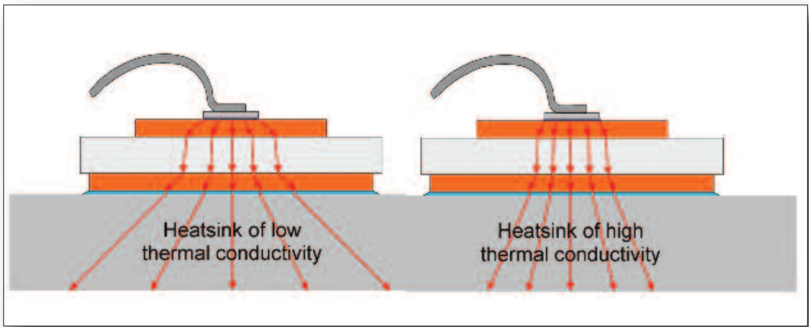

Figure 6: **Thermal spreading with low (left) and high conductivity heatsink (water cooled)**

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.

Figure 5 shows reliability data standardized to a DBC module with Al_2O_3 DBC. Test conditions for all three modules were equal. Also the chip size and number of chips were the same. The temperature difference of each cycle was 100K, starting from 25°C to 125°C. The failure criteria was an increase of $R_{th(j-c)}$ of 20% 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.

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. Figure 6 illustrates thermal spreading in a water-cooled and in a conventional heatsink.

The specifications for all modules are given for a water-cooled heatsink. This means the Rth 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 fewer 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.