Pressure Sintering for Power Modules

Pressure sintering of silver powder is an alternative bonding and joining technology for high temperature applications. Especially large area soldering joins need to be substituted by a more reliable and better performing technique. Those layers are found between ceramic substrates (DBC) and the metallic baseplate which are forming the so-called thermal stack. **Mathias Kock, Danfoss Silicon Power, Schleswig, and Ronald Eisele, Jacek Rudzki, University of Applied Sciences Kiel, Germany**

Typical power modules are building a thermal stack consisting of multiple semiconductors (bare die) on top of a high power substrate (Direct Bonded Copper - DBC) which is assembled onto a copper heatsink (Figure 1). The standard assembly of bare dies, DBCs and heatsinks is a vacuum soldering process for void-free layers with lead-free solder alloys. The use of pressure sintering for the principle assembly of substrates on baseplates has been already reported, but without details of thicknesses and lifetime results, which is the content of this article. The interconnection layer between DBCs and a copper baseplate is produced by pressure sintering of silver powder. To achieve high temperature cycle capability, it was necessary to increase the thickness of the silver layer from normally 10µm to about 100µm. Different layer thicknesses and bonding forces are discussed. The thermal stack demonstrators are exposed to temperature cycles and reliability results are presented. It will be shown how thick silver sinter layers increase the reliability of thermal stacks in advanced applications.

State of the art of bonding and joining

Trends of higher integration and miniaturisation of electronic components into electrical engines lead to increased operating temperatures. In some applications, the ambient temperature already exceeds 150°C. Standard bonding and joining techniques use soft solders and adhesives to connect electrical components to substrates. Some components like power semiconductors even operate at more than 200°C due to power losses and high ambient temperatures. Higher peak operating temperatures result in higher temperatures swings when systems are turned on and off.

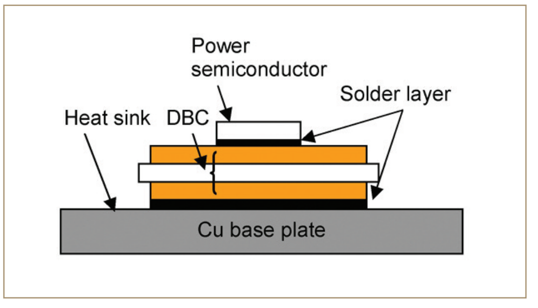

Figure 1: Thermal stack with semiconductor, solder layers, DBC and heatsink

It is well known that soft solders already suffer from rapid degradation above 120°C. Temperature cycling and thermal mismatch between components, substrates and heatsinks during operation additionally lead to early cracks in the interconnecting layers.

With thicker solder joints, the growing of the cracks can be reduced. Ultrasonic scans of a demonstrator with a DBC area of 23mm x 18mm soldered on a 2.5mm thick Cu baseplate (35mm x 60mm) reveal the cracks in the solder joint. Figure 2 shows the crack propagation for a different number of temperature cycles (-40°C to 125°C, 30min dwell time) and two solder layer thicknesses (200 and 400µm). Dark areas are solid solder layers, light green or red areas are indicating cracks in the solder layers.

As a result of thicker solder layers the thermal resistance of the module (R_{th}) increases. A simple thermal stack analysis reveals the different junction temperature rise for 100W of dissipated power (die size 8mm x 8mm) with SnAg3.5 solder (TC = 47 W/mK).

Additionally, with increased solder layers the process stability decreases, because the DBC tends to tilt during the solder process. Tilted DBC substrates are root cause for early cracks in the solder layer due to the critical low thickness. Often specific and costly tools and processes are

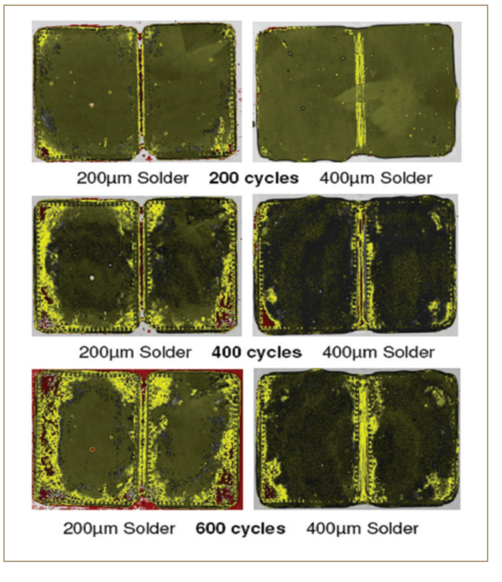

Figure 2: Growing cracks, subject to solder thickness and number of temperature cycles (Ultrasonic imaging by Sonoscan, TU-Dresden)

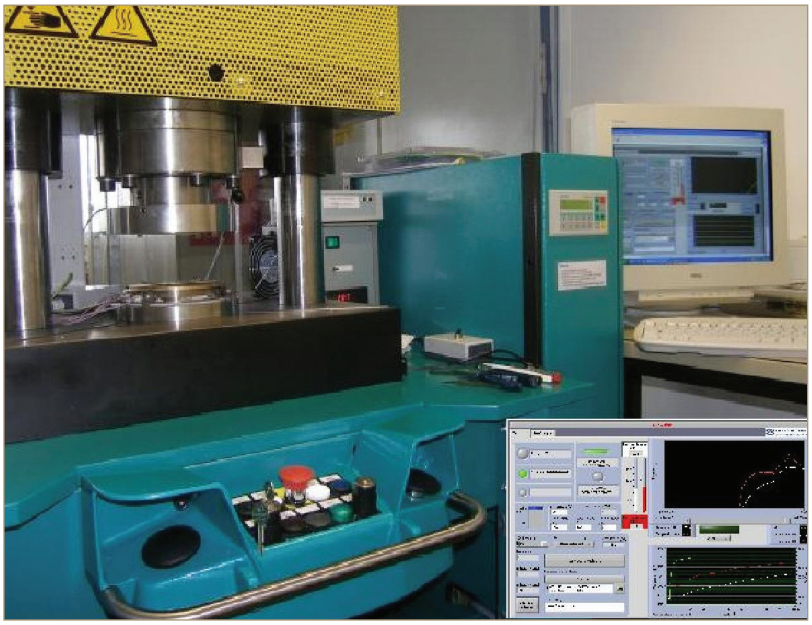

Figure 3: Pneumohydraulic high precision 2-column press (500kN) with an electrical heater in the bottom punch and parameter monitoring equipment

necessary to keep the substrate in place and in correct orientation during the soldering process.

Pressure sintering

Pressure sintering of silver powder known as LTJT (Low Temperature Joining Technique) can be used to assemble power electronics modules. The basis for the bonding and joining process is powder made from idle materials like silver.

The silver flakes offer spontaneous sinter ability at a temperature of above 220°C. The pressure enhances the sinter ability tremendously, due to the increased active contact area between the individual silver particles. To prevent the silvers from sintering at room temperature, the silver flake is enriched with an organic additive. Decomposing of the organic coating around the silver flake takes place at a temperature of above 220°C under oxygen atmosphere. Heating above the decomposing temperature, higher pressing and longer sinter processes support the sintering process of the LTJ silver flakes. The usual sintering process is carried out at 30MPa of force, 250°C for 1 minute and results in a porosity of the sintered silver layer of about 15%. It is necessary to provide an oxide-free surface of the components to be joined for sufficient adhesion forces. A Ni diffusion barrier and Au finish provide sufficient oxide-free surfaces for further LTJ joining processes.

To apply the powder to the surface, several layering techniques such as spraying, screen or stencil printing and transferred preforms are usually applied. These techniques differ in the cost of coating and in their risk of correct application in terms of homogenous thickness and the absence of agglomerations.

To perform the sinter task, a 500kN press is used (see Figure 3). The bottom punch is equipped with a heating unit and the top punch has a rubber fill to assure uniform pressure for the joined elements. The process is computer controlled and monitored for temperature, force and path lengths of compression.

Bond strength qualification

To determine the bond strength of the silver powder connection a peel test was performed.

First, a silver stripe with a thickness of 100µm was joined to the DBC substrate (metallised with Ni/Au, see Figure 4). Then the sample was attached to the sliding support, and the free end of silver stripe was pulled up while the peeling force was measured. The sliding support assures a constant peeling angle during the test phase.

Cohesion fracture within the silver layer is shown in Figure 5. This fracture morphology indicates that the interfacial strength between the sintered Ag and Au metallisation was higher then the strength of the sintered Ag layer. Left picture (after the peeling test): The surface of the DBC was covered with a layer of thin sintered silver. This type of crack is typical for high pressure and a sintering temperature over 220°C.

he typical peel force for this kind of fracture amounts to about 6N/mm (force/stripe width). If the adhesion forces are lower or equal to the cohesion forces then the fracture path can be similar as shown in Figure 5 (right picture). In this case, the peel strength is usually lower then 6N/mm. Numerous voids without sintered silver are to be seen on the peeled DBC surface. High process temperature, high pressure and long process duration improve the diffusion bonding forces within the Ag sinter layer, as well as the interface between the Ag and Au metallisation.

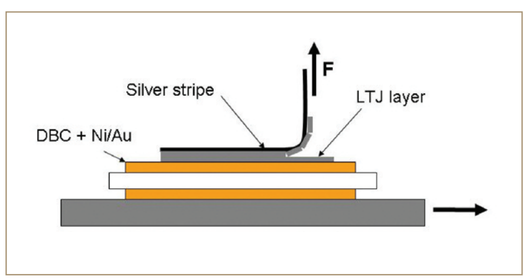

Figure 4: Sliding peel-test with constant angle of the pulling force

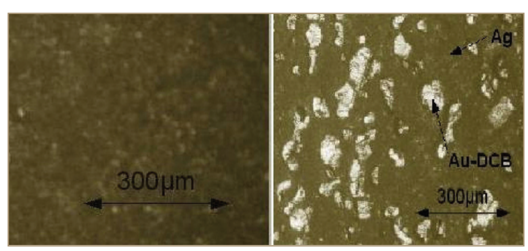

Figure 5: Optical microscope image of cohesion fracture on the DBC substrate with low pressure (right), adhesion and cohesion fracture on the DBC substrate with high pressure (left)

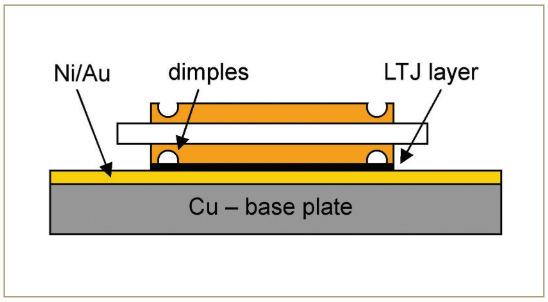

Figure 6: Cross-section of the test sample

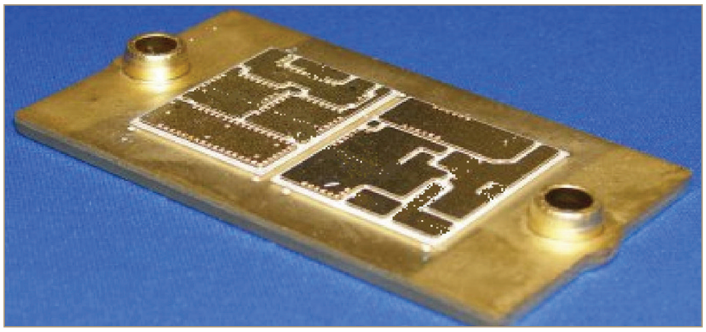

Figure 7: Test sample. Copper baseplate and DBC substrates with Ni/Au metallisation

The results from advanced soldering processes reported above do not meet all of the industrial requirements. Thermal and mechanical properties still need optimisation in terms of R_{th} and thermal cycle capability. Automotive applications, like electric power steering, hybrid electric traction and DC/DC conversion especially require a relatively high thermal cycle capability. This means - small CTE mismatch between substrate and heatsink respectively, and high shear strength of the bonding layer. A perfect design should also offer the lowest possible R_{th}. With an assembly of DBC-substrates and heatsinks by a silver based pressure sintering process both requirements can be fulfilled.

Test specimen

A test module based on the automotive electric power steering module (see Figures 6 and 7) was designed; for comparison an aluminum baseplate alternative to a copper plate was used. The mechanical and thermal connections were realised by the LTJ-layer in the pressure sintering process. To find out the dependency between the LTJ-layer thickness and the module reliability thicknesses of 25, 50 and 100µm respectively were analysed. To assure oxide-free surface areas for the joining process, a Ni/Au metallization was deposited for DBC substrate and baseplate. The LTJ layer was applied by using the transfer/preform method.

The temperature cycling test (-40°C to 125°C, EN 60068-2-14) was applied to analyze the reliability of the test samples. Test samples were arranged in pairs and torqued together back to back, in order to reproduce the final mounting the power modules to the heatsink. The temperature cycling test was performed periodically in two thermal chambers, whereas the dwell time was 30 minutes. After 500, 1000 and 1500 cycles, the temperature test was interrupted and the sintered layers were inspected. To detect the fracture within the sintered silver layer, the ultrasonic microscope method was used. For precise investigations of the joining layer in the edge areas, additional cross-sections were prepared.

Results

Figure 8 shows a selection of ultrasonic images of the test samples. In samples with 25µm silver sinter layer thickness large fracture areas already after 500 temperature cycles are to be observed. By using Al instead of Cu baseplates, a small improvement regarding crack propagation is visible. It could be explained with the smaller young's modulus of the aluminum compared to copper. Samples with 50µm and 100µm LTJ layer thickness only show small fracture areas, even after 1500 temperature cycles. These cracked areas are significantly smaller than the observed cracks in large area solderings (see

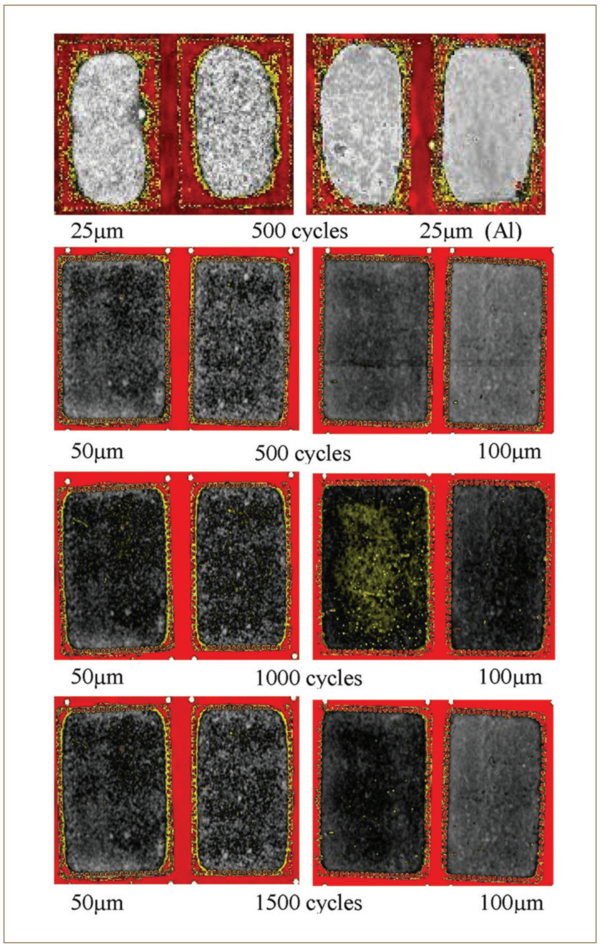

Figure 8: Ultrasonic scans of the joining layers

Figure 2). This confirms the very good reliability of the test samples using LTJ technique. Due to the good results, the test is continued in order to find the limits for the given DBC size and LTJ layer thicknesses.

Conclusion

The LTJ-technique is capable of withstanding at least 1500 temperature cycles which is a factor of 10 higher compared to standard solder layers (100µm), and a factor of 4 higher compared to advanced process with 400µm. Together with published results about promising high number of power cycles, it now seems to be possible to manufacture high reliable power modules even for high ambient temperature conditions. In the near future, further investigations are planned regarding different dimensions of the DBCs and thicknesses of the copper plate in order to improve the understanding of crack building principles. A second issue for future activities is the die assembly on a DBC, as well as the DBC-on-heatsink assembly in a single step.

Literature

Pressure Sintering for Thermal Stack Assembly, Proceedings of PCIM Europe 2007