Improved Thermal Transfer For Power Modules

A Science on its own

Modern power semiconductors need an efficient and reliable cooling. The connection between the power module and the according heat sink is both, centerpiece and bottleneck at the same time. Here, often materials are in use that cannot cope with the demanding environment found in power electronic applications. Infineon has decided to cooperate with Henkel Loctite to create an interface material especially dedicated to power electronic modules.

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During the design phase of any power electronic equipment, special care has to be taken regarding the thermal aspects of power semiconductors. Temperature swing along with temperature levels forms the basis for the estimation of a useful lifetime of the design. The thermal resistance between semiconductor and heat sink as a consequence of the thermal interface material in use is of major importance. It has to be as small as possible and, in best case, may not change throughout the predicted lifetime. Developers tend to use a simulation based on datasheet values given for a thermal grease. Assuming a homogenous layer between semiconductor and heat sink, a simplified model can be extracted that usually is of conservative nature.
To predict, what options can be considered to refine a thermal interface material, this simplified model turns out to be inappropriate. Several important parameters are not included. To demonstrate the drawbacks of the simplified model, figure 1 hints out an extended version.

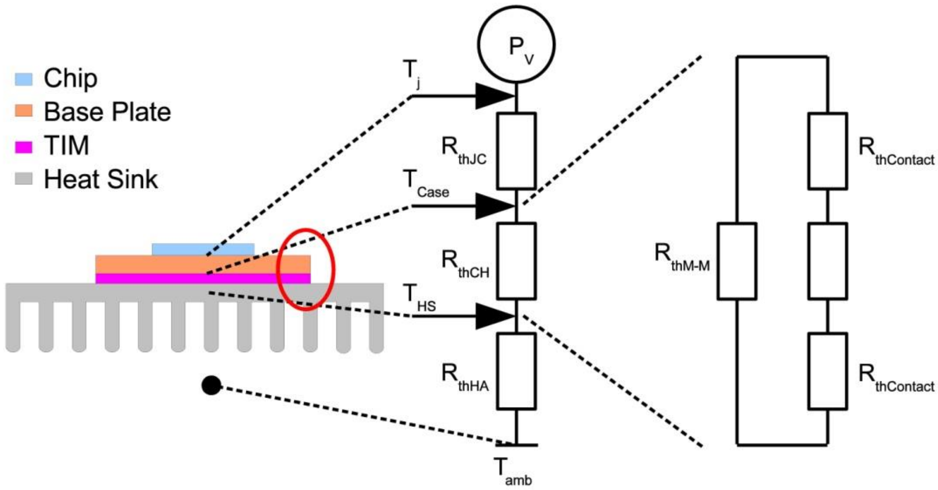

Figure 1: Sketch of the setup, simplified model and extended model of a power electronic system

The transfer path from the Chip to the base plate R_{thJC} and the thermal resistance from the heat sink to ambient R_{thHA} are given by the chosen materials. An improvement cannot be achieved without changing these materials.
However, from the extended thermal model given in figure 1, possible alternatives to optimize the thermal interface material can be derived:

- The thermal conductivity has to be maximized to reduce the bulk resistance R_{thTIM}
- Combining proper materials allows for a reduction of the contact resistance RthContact between metal surfaces and the thermal interface material
- Achieving largest possible areas that feature metal-to-metal contact with low R_{thM-M} is highly desired. Therefore a local variation of volumes applied is necessary, accompanied by smallest possible layer thicknesses.
- The final system has to remain stable over the whole lifetime that is predicted for the application. It has to be immune regarding thermal mechanical load, capillary effects and drying.

Additionally, the material has to be conformal to RoHS, free of silicone and electrically nonconductive.
Recent developments in the area of phase changing materials have been the decisive factor, to continue research in this field.

Improving thermal conductivity
The first step leading to an optimized solution is the improvement of the bulk conductivity of the raw materials. Copious tests were done and a multitude of different materials was generated for tests and measurements. Figure 2 depicts four steps taken during this development phase.

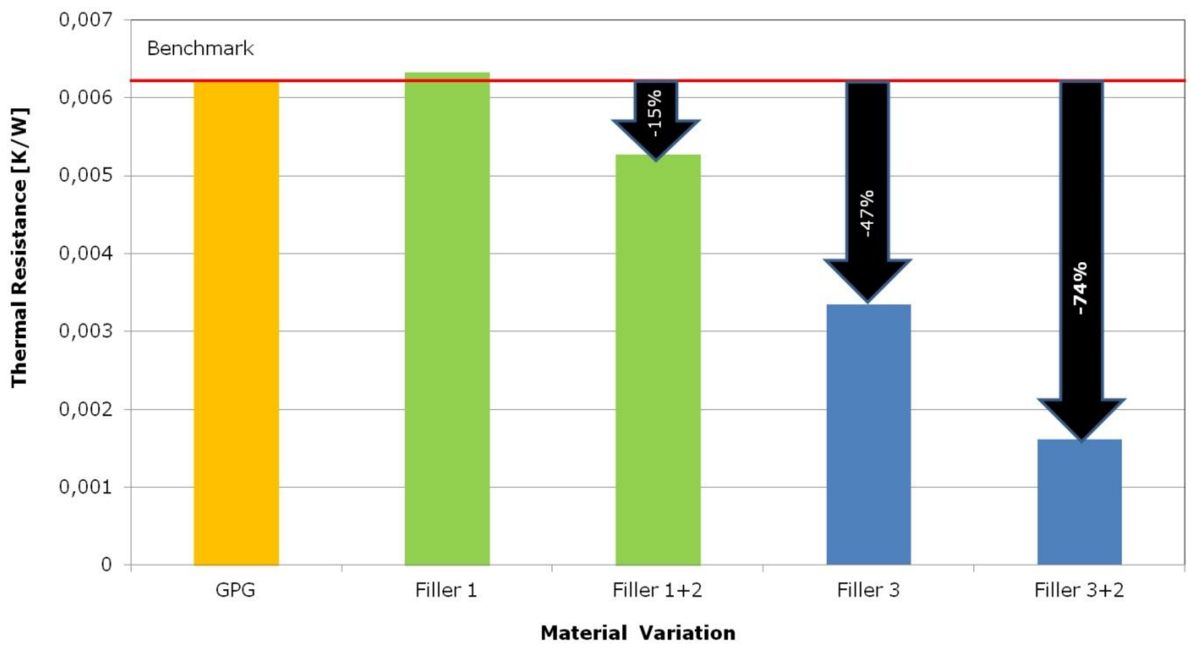

Figure 2: Comparing thermal resistances of a common grease and several new materials

The General Purpose Grease (GPG) is a material widely used and accepted in power electronic applications, therefore it is considered as a reference. It can be concluded from the diagram, that the choice of fillers and combination of different filler systems lead to the desired improvements. The test results are generated according to ASTM 5470-12. Using the available Filler1, the first material was not able to outperform the reference. By blending the material with a second filler with a different particle size and particle size distribution, a bimodal system is created featuring improved thermal properties. Stepping away from classical ceramic fillers and change over to fillers based on metal oxides lead to a further increase of the thermal conductivity. This approach too benefits from the idea of blending with a second filler. Compared to the reference, a reduction in thermal resistance of 74% was finally achieved.

Minimizing the contact resistance

It can be concluded from figure 1, that a reduction in contact resistance improves the overall system twice. The test done acc. to ASTM is inconclusive regarding contact resistances as the polished surfaces and the pressure applied differ from what is commonly seen in the application of power modules.

Due to cost pressure, industrial designs prefer heat sinks with a milled surface. The roughness of these surfaces is about 10-15µm and therefore in the range of the particle size found in common thermal greases.

To reduce the contact resistance, it is mandatory to generate the largest possible contact area between metal surfaces and the thermal interface material. To enhance the forming of direct metal-to-metal contact at the same time, further features of the desired material can be derived:

1) The maximum particle size has to be below the roughness of commonly used heat sinks
2) The raw material has to be a paste-like substance to enable screen printing. This way, areas predestined to form direct metal contact can remain uncovered.

A schematic overview is given in figure 3 to hint out, how different particle sizes influence the forming of contact areas.

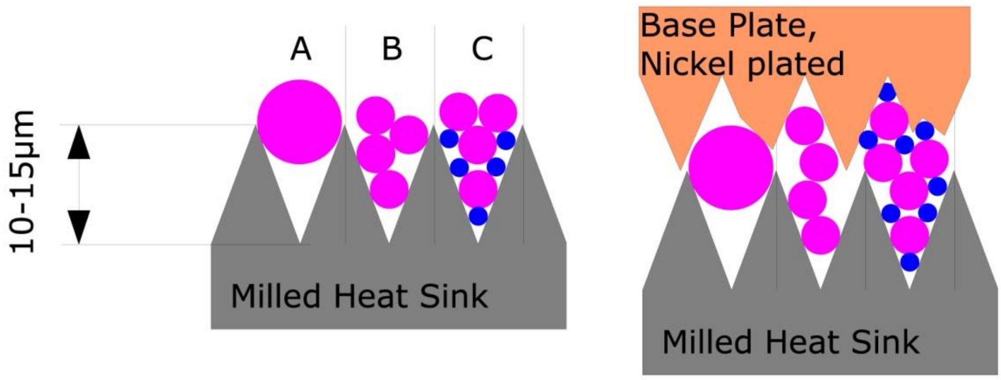

Figure 3: Influence of material properties to the forming of contact areas

A - Monomodal System, Particle size 10µm
B - Monomodal System, Particle size 5µm
C - Bimodal System, maximum Particle size 5µm

The bimodal system generates the largest number of contacts with the surrounding surfaces and therefore the lowest contact resistance. Additionally, the small particles enhance the capability to form thin layers and in turn maximize the areas forming direct metal contact. Both features improve the thermal situation.
Figure 3 also supports an explanation why the ASTM test is incompatible to the application of power modules. The test consists of polished, planar surfaces with a roughness of <0.4µm. A homogenous layer of TIM is applied, controlled by distance keepers. Within the application, these values are never reached, making it difficult, if not impossible, to compare these data.
Power semiconductors greatly benefit from extremely thin layers and massive mounting forces coming from the screws. Both is not considered in the ASTM test.

Besides the material properties, the process of applying the material is of crucial influence. In case the macroscopic geometry of the base plate of a power module is known exactly applying thermal interface material can be done in locally optimized amounts. TIM can be printed to areas where it is needed. Areas that would form direct metal contact, or where TIM would lead to detrimental influences, remain clean. This especially is true for the areas below the mounting screws. Here, direct metal contact is enforced due to the high mounting forces.
As an example, figure 4 contains a picture of an EconopACK™ 4 with TIM applied.

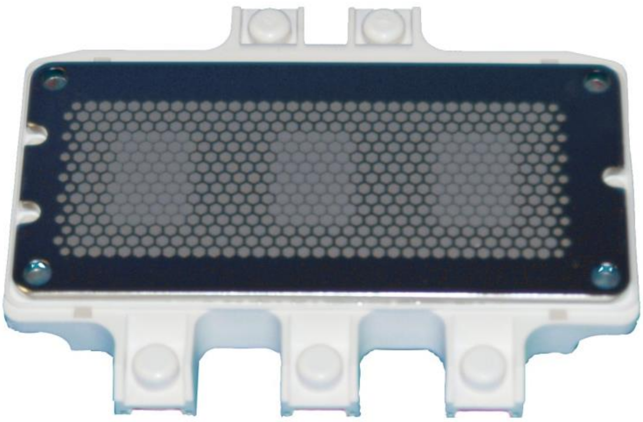

Figure 4: EconoPACK™ 4 with TIM applied. Stencil printing enables the application of locally optimized volumes using inhomogeneous patterns.

As can be seen on the picture, the area around the screws is left without TIM and a larger volume is applied to the cavities below the chips' positions. In addition to detailed knowledge about the base plate's geometry, meticulous control of the printing process is unavoidable. This way, it is ensured, that the printed pattern is accurately aligned and the volume of each single dot is within specification. To achieve this level of precision, fully automated optical inspection systems (AOI) have been installed and every single module is scanned after printing. The precision of the system allows for determining volumes down to far less than 1µm³ per single dot.
Besides the thermal improvement, this method also leads to advantages in mounting and assembly. As no material is applied below the screws, changes due to displacement cannot occur. The torque applied to the screws remains the same even after the TIM has spread. Retightening the screws is unnecessary.

The high filler content of the new material and the special properties regarding the contact resistances are warrantors for the high performance even at the first turn-on, eliminating the needs of special burn-in cycles.

Long-Term Stability

It is of utmost importance for the application, that the thermal conditions remain stable throughout the predicted lifetime. A most prevalent cause of failure is a loss of thermal transfer. Common thermal greases are often pumped away from the hot spots due to thermal mechanical movements or fail due to separation. As a consequence, chip temperatures rise and the thermal stress to the semiconductor increases as well.

An adequate test to substantiate a statement regarding long-term stability is a high temperature storing test (HTS). Each specimen in the test consists of power module with thermal interface material applied, mounted to a heat sink. The initial thermal properties are measured and the specimen is subject to 125°C for one week afterwards. Again, the thermal properties are measured; the cycle repeats until 1000 hours at 125°C have been completed.

After the development of TIM has lead to a final material that has survived all qualification tests within Infineon, a further test in a real Inverter provided the final result.

An accelerated test was conducted that was set up to simulate an operating time of 150.000 hours within 1000 hours of testing, representing 20 years of lifetime. The end of life criteria chosen was a maximum chip junction temperature of 150°C as beyond this the semiconductor would be operated outside its specification.

The diagram in figure 5 summarizes the results gathered.

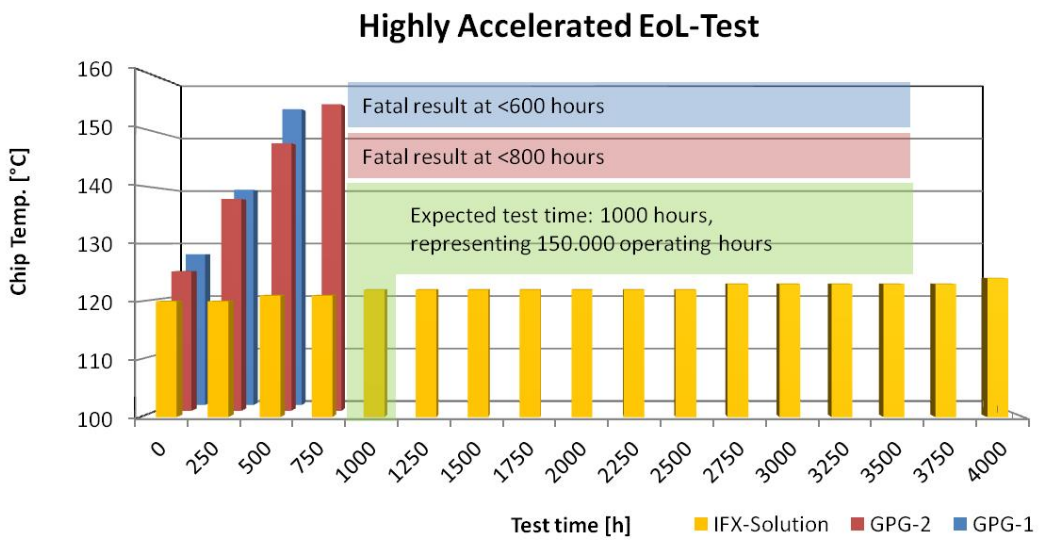

Figure 5: Results from the accelerated stress test, simulating 20 years of operation

With the general purpose grease (GPG-1), the first test run was terminated after less than 600 hours with fatal results. The term “fatal” refers to the total destruction of the semiconductors due to massive overheating.

A second test with a common material achieved almost 800 hours, the result remained the same.

The material created by Henkel Loctite and dedicated to Infineon power modules lead to the lowest temperature from the beginning. Most noteworthy remains the fact, that the test was discontinued after 4000 hours without failure.
Due to the exponential correlations, this resembles far more than four times the expected lifetime.

Conclusion
Modern power semiconductors have reached a state of development demanding a holistic approach to all components involved in setting up efficient inverters. From the often underestimated topic “Thermal Grease”, a high performance material arose that now has significance similar to other functional layers as for example solder joints connecting chips to substrates.
The loss of thermal transfer capabilities is among the failure causes most often observed. This may also be a consequence of increased lifetime expectations and higher power densities.
Using dedicated materials and releasing customer’s assembly lines from the process of applying thermal grease is a logical step to cope with the growing demands in power electronic designs.