Optimizing Thermal Interface Material for the Specific Needs of Power Electronics

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Abstract

Thermal interface material (TIM) is a key component in the majority of power electronic systems. Heat, generated by the semiconductors, has to be transferred to a heat sink and finally dissipated to ambient. The solutions available today focus on applications like computer processors, mobile applications and discrete electronic devices. Though similar local power densities need to be handled, power electronics for industrial inverter applications based on power modules have different needs. The present paper deals with these needs and describes the steps in developing a thermal interface material, especially dedicated for the use in power electronics.

1 Introduction

Whenever two surfaces have to get in contact with the purpose to transfer thermal energy, the imperfections within the surfaces need to be treated. Surface parameters like bow, cavity and roughness are among the first things to be considered. In a simplified model, there are two parallel paths forming for thermal energy transfer as depicted in figure 1.

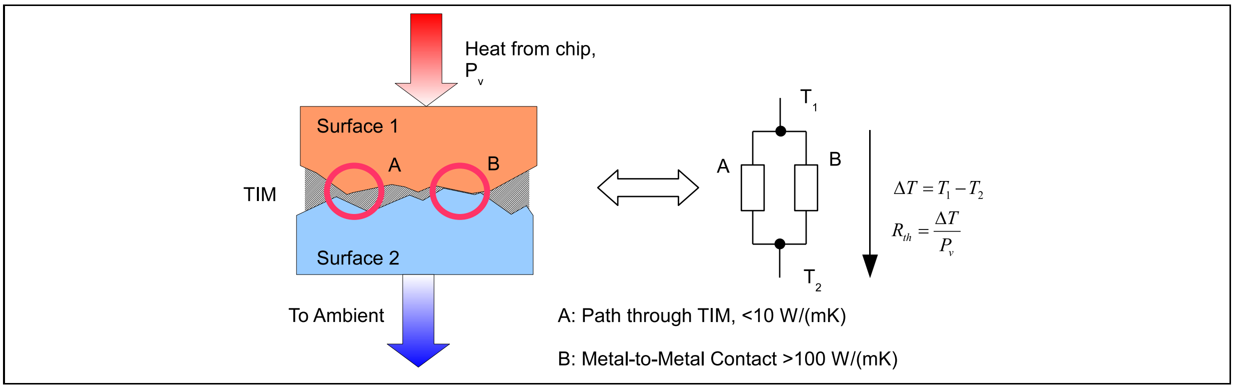

Figure 1: Microscopic view of thermal transfer paths connecting two different metallic materials

From the picture, a number of features for TIM to minimize the thermal resistance R_{th} can be determined:

- Obviously a high thermal conductivity for TIM is necessary
- TIM may not prevent the forming of metal-to-metal contact as this path provides the highest thermal conductivity
- A reduction of the contact resistance from Surface 1 or Surface 2 to TIM demands excellent wetting abilities and large contact areas
- Increasing contact areas can be achieved by using small particle sizes
- Smallest possible bond lines have to be achieved; TIM needs to provide proper flowing abilities

Besides these basic properties, other parameters need to be considered for the application targeted:

- Long-Term stability is of major importance
- The material has to be conformal to RoHS and non-toxic
- Silicon-based materials are not an option
- Electrically, TIM has to be non-conductive
- For mass production, a printable material is preferred

Some of the demands towards the material are contradictory. A printable material needs to have a paste-like appearance. Good wetting capabilities in paste-like materials usually are accompanied by low viscosities. It can be observed, that materials with low viscosities tend to be pumped out in the application, thus reducing the thermal transfer capabilities. Furthermore, open gaps or channels forming during the operation speed up the ageing process [4]. From the materials available to the market, none has shown an appropriate performance in all the test and at the same time fulfilled the criteria listed above. The option left was a cooperation between power module manufacturer and thermal interface supplier to specify and create a suitable material. To achieve the desired performance, a detailed understanding of the application *Power Module* is mandatory.

2 Power Electronic, Power Density

Computer processors today can be seen as an application with high power densities. A modern CPU can consume as much as 130W of power on an area of 263mm^2 representing a rectangle of 16mm in width [1] and a power density of about 0.5W/mm^2. Thermal grease is needed here too to get good thermal connections between the processor core and the heat sink attached. The vast amount of processors sold is the reason for grease manufacturers to tune grease for this application, especially as processors and larger discrete packages have similar footprint sizes. It is often concluded, that grease works under the condition described by thermal swing regardless of the application. However, the demands in power electronic differ from those in personal computer, notebooks or mobile phones, demanding a dedicated solution. A brief comparison hints out some of the main discrepancies:

	CPU	IGBT
Chip Area $[mm^2]$	263	190
Power Density $[W/cm^2]$	50	100-200
Force applied to heat sink	Several Newton	Several kilo Newton
Thermal Cycling demand	None	Large
Expected Power Cycles	None	> 100.000
Expected Lifetime [Years]	< 5	$10 \ldots 30$
Cost of replacement [US$]	< 200	$10^3 \ldots 10^6$
Ambient Temperature $[^oC]$	$20 - 40$	$-50 \ldots 65$
Case Temperature $[^oC]$	< 75	$85 \ldots 110$

Due to these differences, the thermal interface is far more crucial in power electronics than in any other application. To achieve better thermal performance, extended research is done to optimize the base plate of module designs [3]. Still, it would be short-sighted to conclude that general purpose materials that perform well on a CPU perform equally well in power electronics as both thermal stress and long term issues cannot be compared. Additionally, thermo-mechanical stress applied to thermal grease becomes a topic in power modules and needs to be examined closely.

Figure 2 acts as a base to explain the differences.

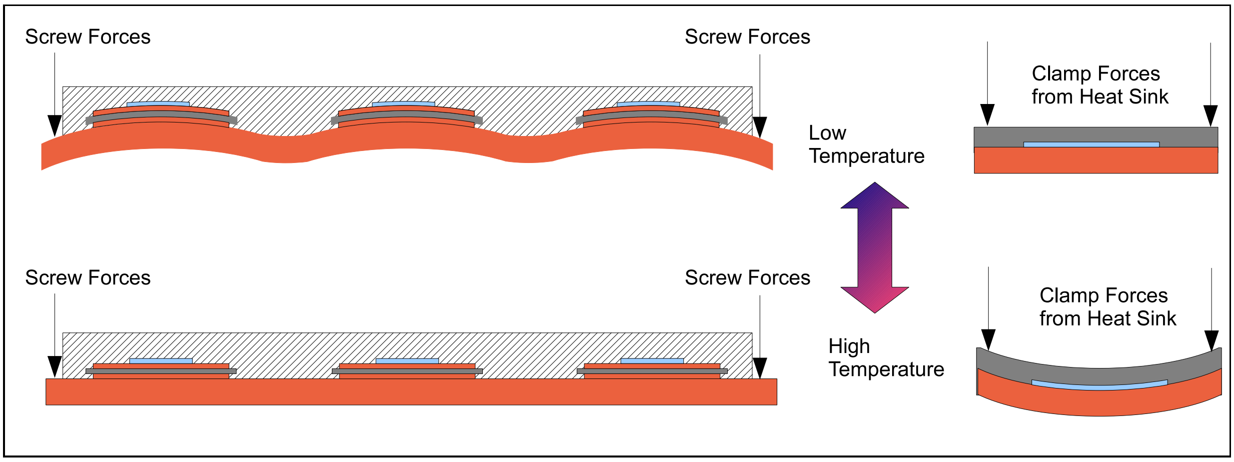

Figure 2: Comparison of thermo-mechanical movement in power electronic modules and discrete parts or CPUs

Discrete components like a CPU only have a contact area to the heat sink of about $4cm^2$. A change in thermal conditions may lead to a change in volume across this area, however the size of the cavity forming this volume is minute. Due to bimetallic effect, the discrete component changes its shape from plain to convex.
On a power module, base plate sizes of up to $19 \times 14cm^2$ have to be considered [2]. To improve thermal performance, the baseplate may not be plain in cold conditions. Here, as a consequence of the bimetallic effect, the base plate gets close to plain shape in high temperature conditions. Even if the height of the cavity is the same as the one formed above the processor, the volume grows with the footprint leading to 60 times the change in volume. An additional factor is the temperature swing that has to be considered. It is safe to assume that due to the larger swing the change in volume below a power module can be 100 times as big as on top of a single CPU.
As the lifetime expectation for power electronics is supposed to be 5 to 6 times the lifetime of a personal computer, it becomes obvious that TIM has to have advanced qualities in this field of application.

3 Material Optimization

The resulting material achieved by copious development is a non-silicone, modified hydrocarbon phase change base system. Combined with specific stabilizing agents, it provides both the enhanced thermal performance and the oxidation resistance needed to cope with the lifetime expectation within the power module environment. This modified system, despite being solid at room temperature, retains enough surface softness to easily conform to the non-planar contact surfaces present at the initial module-to-heat-sink assembly. Over and above existing and advanced phase change compounds this IFX compound was developed with specific targets:

- Improved thermal contact and bondlines
- Pre-application without preheating
- Matching the particular needs of power electronic modules

Secondary but beneficial properties of the compound are:

- Simple re-workability and cleaning without the use of solvents
- Cost savings due to module specific printing patterns minimizing the amount

The initial contact takes place with no pre-heating or burn-in required, so that there is adequate thermal contact for the first power on cycle of the module. With a melt point in the range of 45^oC, the material remains as a solid coating under normal handling and storage conditions, yet quickly melts during powered operating conditions to fully wet all contact surfaces. Unlike thermal grease which remains wet and is prone to collecting dust or smearing after application, this optimized phase change thermal interface material is completely dry-to-the-touch on the completed module prior to it's shipment to the end customer.

3.1 Matrix - Filler interaction

First, several high performance fillers were selected. Examinations were conducted to determine the best combination of filler types, shape and particle sizes. Additionally, overall filler loading levels and distributions were determined to achieve the optimized bondlines as desired. The developement lead to a multi modal filler system which was blended to cope with the major requirements:

1) achieve a high thermal contact rate even when cavities between module and heat sink caused by base plate unevennesses are present
2) establish high rates of metal-to-metal contacts between base plate and heat sink
3) provide the best possible filler blends to reach outstanding thermal contact even at medium layer bondlines

Any blend of particles in a fluid matrix will have a degree of trapped air [7]. Hence both the compound and fillers were formulated in a way to minimize the presence of air voids in the vicinity of the particle-compound point interfaces. As the diagram in Figure 3 hints out, significant changes to the application specific thermal resistance were achieved by blending two thermally conductive fillers into a bi-modal distribution and again by altering the ratio of particle sizes of the two filler types.

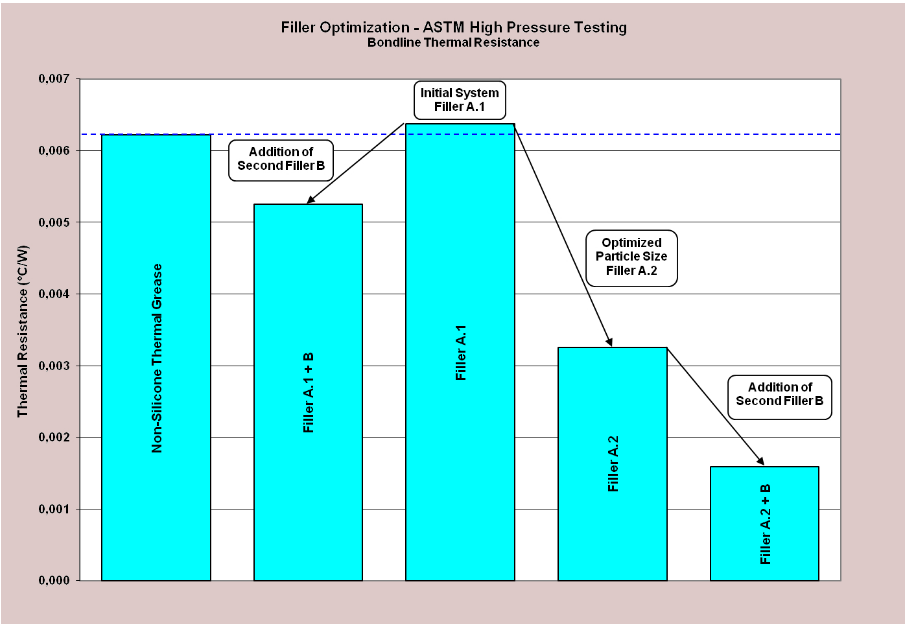

Figure 3: Evolution leading to the new solution using different material compositions, general purpose grease as a reference to the left

A commercially available thermal grease, widely used in the field, was set as a benchmark to reach. The material chosen has proven acceptable for the use with IGBT modules in actual field use during the last years. A single filler system was established using a new, high performance thermal filler labeled Filler A.1 which gave very similar performance to the benchmarking grease. Blending this filler with a second one with small particles, labeled Filler A.1+B yielded a reduction in thermal resistance of roughly 15% compared to the grease. Further optimisation of the single filler system was achieved by moving to a smaller particle size of the type A filler, see Filler A.2, which resulted in a 47% reduction in thermal resistance over the grease. The most significant improvement came from blending the two filler types - Filler A.2+B - to yield a 74% reduction in thermal resistance.

In order to enhance the flow and wetting properties of the materials, various wetting or coupling agents were evaluated as well. Of all the variants considered, the most appropriate method of determining the thermal performance was determined to be the application specific thermal resistance as derived through direct contact test methods. The specific bulk thermal conductivities of the evaluation materials were not primarily viewed as the key driver. Actual thermal performance, as delivered on large contact area devices when operating under realistic pressures and wattages, was considered to be more substantial.

3.2 Viscosity and Rheology

The viscosity of the compound before drying is such, that low speed/high pressure settings are recommended to achieve good roll and aperture fill. A low release speed is required to achieve release from the apertures after printing. Fig. 4 displays the printing of a power module. The material is developed to allow prolongued working intervals before cleaning of the underside of the stencil is necessary, thus supporting mass production.

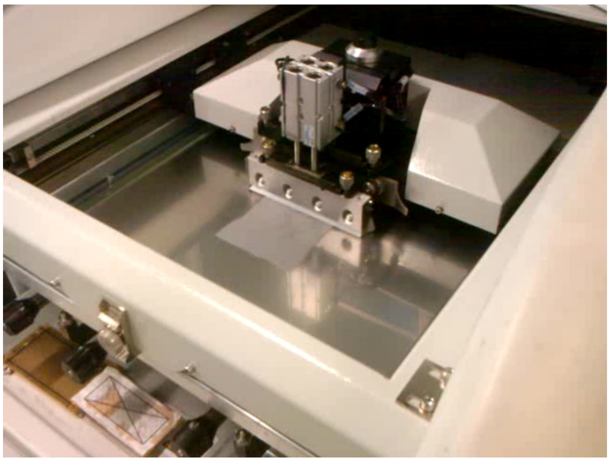

Figure 4: Excellent printing results with several hundred units between cleaning

The viscosity of the compound at warm-up aims at optimised wetting behaviour. The matrix-filler composition also copes with the objective of achieving a high thermal contact even before first warm-up. With effective cold contact, temperature overswings at first warm up also were eliminated; measurements have shown that the temperature levels remain below those reached with thermal greases already available and widely used. This final, optimised phase change compound was selected from the various design elements and successfully subjected to long term reliability testing [8].

3.3 Drying and Pre-application

A solvent was formulated to allow the compound to dry within a specific time frame since drying is required for optimal thermal performance. After drying, the phase change compound remains pre-applied, solid and tack-free dry to the touch. Thus handling and assembly is easy and without mess, allowing cost and time savings. An adequate drying time had been reached which still allows for a long abandon time within the printing process. The developed compound is suitable to be used in mass production environments as a means of accurately applying it in an automated manner.

4 Measured Results

Several methods have been described to apply stress to the thermal interface layer in order to get a reliable statement towards thermal performance and long-term stability. As described in detail in [8], storing the material at high temperatures is one way. The advantages of this test are the relatively short test duration of about 40 days and the reliable result. Figure 5 summarizes the different behaviours regarding several different materials.

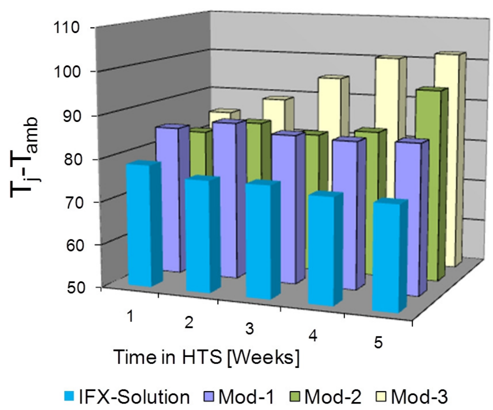

Figure 5: Different ageing effects in different TIM-compositions

The material MOD-3, set as a benchmark, shows continuous degrading of the thermal transfer capability. MOD-2 keeps up well for several hundred hours but fails the 1000h criteria. MOD-1 shows a quite stable behaviour but is thermally outperformed by the new IFX-solution.
HTS-testing however does not apply stress due to temperature swing. This is generated in two further tests. Active power cycling is done with high temperature swings to induce thermo-mechanical movement on both, high temperature swing and high temperature levels. In a further test, a laboratory inverter was subject to highly accelerated life time testing (HALT). In this second test, 1000 hours of operation resemble, according to the thermal model, almost 20 years of lifetime. The results from both tests are included in figure 6.

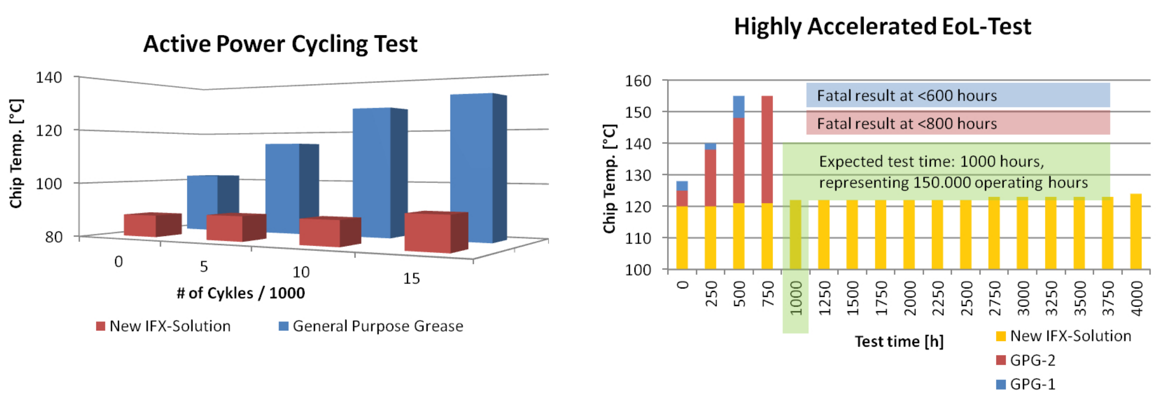

Figure 6: Results from Active Power Cycling to the left and HALT-Test to the right

The term "'Fatal Result"' in the graph refers to the destruction of the power semiconductor in use due to thermal effects. It can be concluded from these results, that the new material is well suited for the needs of power electronic modules in both thermal performance and long-term stability.

Conclusions

The joint efforts done in understanding mechanical, electrical, chemical and thermal aspects along with the needs of the final application were necessary to specially design a dedicated thermal interface material. Just as the improvements on interconnection technologies [5][6], an interface material that is excellent in thermal performance along with outstanding long-term stability is mandatory. Modern power electronic designs have to be optimized in every aspect and thermal management becomes more and more a key parameter in this application. With the new TIM introduced lately, designers can now count on a reliable, well tested material that eases the challenging task of all thermal aspects in power electronics.

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