The Thermal Heat Sink Interface of IGBT Modules w/o Base Plate A Comprehensive Experimental and Simulation Study

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Abstract

The thermal interface between power modules and heat sink is studied in detail by means of a new set-up enabling the simultaneous measurement of thermal resistance and thermal grease thickness. The design of the set-up is studied in detail and various measurements enabled by this new equipment are presented. Among these are the module mounting process and the mechanical behaviour of the grease layer under power cycling conditions. From comparison with simulations the presence of a thermal contact resistance between module or heat sink, respectively, and grease is derived and the thermal interference of neighbouring chips is investigated.

I. Introduction

While the measurement of an electrical resistor value is quite trivial, the evaluation of thermal resistances R_{th} is still linked with a couple of definition-, theoretical- and practical difficulties [1]. In case of power semiconductor modules this is especially true for modules based on direct copper bonded (DCB) substrates without a massive copper base plate. For modules with base plate the characterising R_{th} is generally accepted to be given by the junction to case thermal resistance $R_{thjc} = (T_{vj} - T_c) / P$ where T_{vj} is the virtual (i.e. indirectly determined) junction temperature, T_c is the case temperature at the bottom of the module directly below chip under test and P is the dissipated power. For modules without base plate, however, the measurement of T_C is hardly possible. As a consequence of limited thermal spreading the presence of a thermal sensor will heavily disturb the thermal system. Thus the measurement of R_{thjc} will yield erroneous results. Therefore the junction to heat sink thermal resistance R_{thjh} has become the accepted value representing the thermal properties for modules without base plate. This approach, however, suffers from the fact that the thermal grease layer contributes a substantial share to the measured value. Besides of the material properties of the selected grease material its thickness is crucial for the measurement result. This has been the motivation for the development of a new experimental set-up capable to measure both, thermal resistance R_{thjh} and grease thickness simultaneously. In this article, first we introduce the newly developed set-up, then demonstrate how the influence of the grease thickness may be eliminated from the measurement data, compare the experimental with simulation results and use the equipment to quantitatively investigate phenomena like the module mounting process.

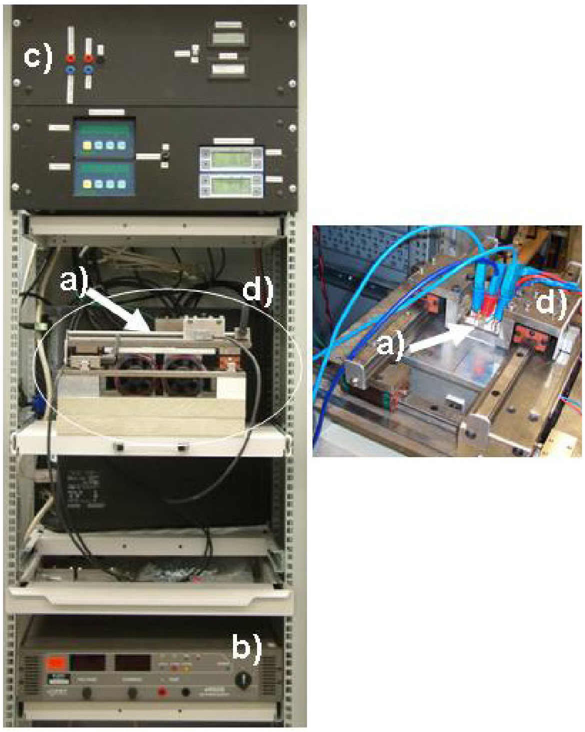

Fig. 1: Experimental R_{th}-setup. The left photo shows the 19'' rack in total. On the right a detail view of the module positioning unit is shown. Details see text.

II. Experimental set-up

A photo of the measurement equipment is shown in Fig.1. In general the equipment equals the set-up usually used to determine thermal resistances of semiconductors: The device under test (DUT) (a) is heated up by a current pulse (10-30s) from a high current source (b). The heating power is simply calculated as the product of on-state voltage at the DUT and current. Within the control rack (c) the current pulse is turned off fast (t < 1 µs) with help of an auxiliary IGBT switch. Afterwards, only a small probe current from a constant current source flows and the voltage at the DUT under this small current is measured as a function of time. With help of a separately done calibration the transient may be translated into a junction temperature transient. Simultaneously, the heat sink temperature is measured by a thermocouple immersed into the heat sink just below the centre of the investigated chip. The positioning of the module on the heat sink is simplified by a positioning unit (d). Simultaneously with the thermal measurement the thickness of the thermal grease is measured by two sensors in line with the thermal sensor. To avoid complications with a mechanical distance measurement we use inductive sensors (supplier µε) detecting the influence of eddy currents within the modules bottom copper (or metal) layer on a coil's impedance (Fig. 2).

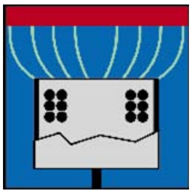

Fig. 2: Schematic principle of a distance sensor based on eddy currents: Within the sensor a coil generates an RF magnetic field which induces eddy currents in the probe (red). The impedance change in the coil is a measure for the probe-object distance [2].

All measured data are recorded with help of a fast A/D converter PC card. The whole measurement is controlled from a computer using a self-developed LabView® program code.

III. Geometric design details

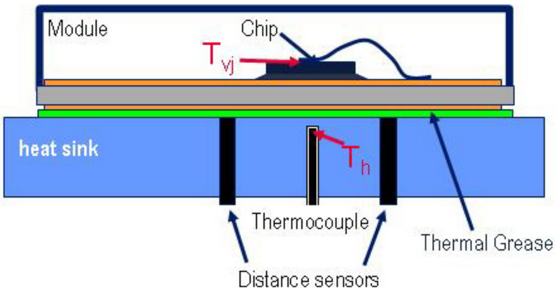

Fig. 3: Schematic of the measurement principle: The virtual junction temperature is determined indirectly trough an electric measurement. A thermocouple immersed into a drilled hole measures the heat sink temperature below the chip. The thermal grease thickness is determined by two distance sensors.

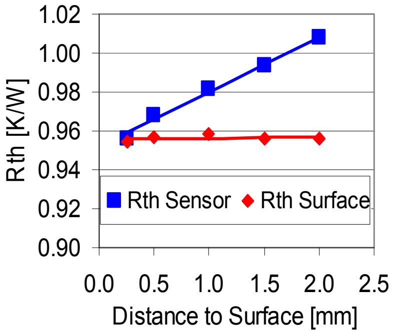

Fig. 4: Simulated influence of sensor depth on T_h measurement. Details see text

In Fig. 3 the experimental set-up is sketched: A power semiconductor module is placed with the chip under investigation atop a thermal sensor buried in a heat sink. At a distance of 6 mm each, two inductive distance measurement units are placed to determine the thickness of the thermal grease.

For the design of the set-up the placement of the thermal sensor within the heat sink below the chip has to be considered carefully. To obtain a result almost independent from the heat sink used, the temperature has to be measured as close to the heat sink surface as possible. But the position shall also be far enough from the surface to ensure an almost undisturbed heat flow. Therefore the dimensioning of the drilled hole in the heat sink designated for the thermocouple has been simulated by a finite element approach.

In Fig. 4 the simulated R_{thjh} of a 42 mm² chip is shown. The blue curve represents the R_{thjh} when the temperature is measured at the end of a hole of 1 mm diameter drilled vertically from the bottom of the heat sink. This simulates the result obtained experimentally when the temperature is measured by a thermocouple immersed into such a hole. The red curve shows R_{thjh} when the heat sink temperature is measured (by simulation) just at the heat sink – grease interface. It can be concluded that at a realistic distance of 1 mm between top of the hole and heat sink surface the difference between measured R_{thjh} and the "ideal" R_{thjh} is negligible, i.e. the systematic error will be not more than +2%. With a second simulation the dependence of the result from the drill diameter has been investigated, as well. The result is that a drill diameter of 1mm suitable for the use of standard thermocouples is absolutely uncritical for a proper measurement.

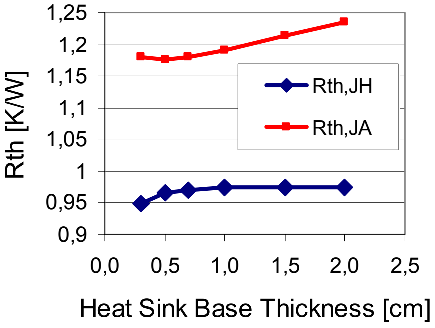

Fig. 5: Dependence of the measured junction to heat sink thermal resistance R_{thjh} and the junction to ambient thermal resistance R_{thja} on the thickness of the heat sink base.

Finally, a third dimension has to be considered: The thickness of the heat sink base. As can be seen in Fig. 5 a thin base of less than 0.5 cm leads to an increased junction to ambient thermal resistance and to a virtually reduced R_{thjh}. This is a consequence of the lack of lateral thermal spreading: A lack of thermal spreading leads to a pronounced temperature maximum below the chip and therefore to a virtually reduced junction to heat sink thermal resistance. A heat sink base thickness of > 1cm, on the other hand, increases the resistance to ambient since it only adds vertical resistance but does not increase lateral spreading any more. Consequently, a base thickness of 1 cm was chosen for the experimental set-up.

Obviously it is not possible to measure both heat sink temperature and grease thickness at the same location. Therefore the grease thickness measurement is performed by two sensors placed in line with the T-sensor at a distance of 6 mm each. The grease thickness above the sensor is interpolated from the two measured values then. This, of course, is only allowed if the distance between heat sink and module varies only slightly and almost linearly over the distance considered. Fig. 6 shows a typical topography of a not mounted DCB-module with a size of 55x38 mm². It is clear that the shape of the surface is quite smooth and the interpolation of the grease thickness from two measured values will yield accurate results.

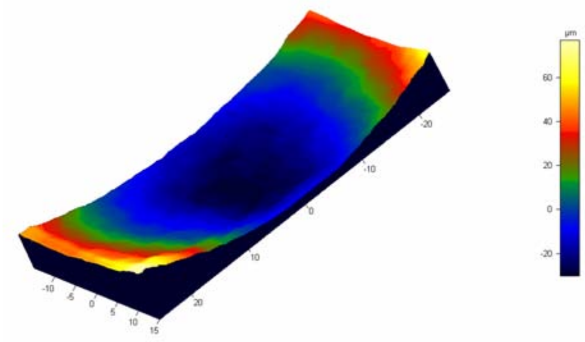

Fig. 6: Typical topography of an unmounted DCB-module. Here, the bending amounts to roughly 60 µm.

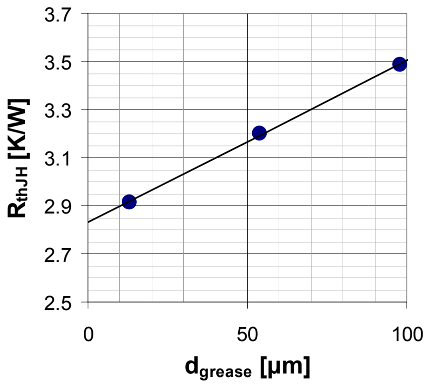

Fig. 7: Measured dependence of R_{thjh} on the thermal grease thickness. The straight line is a linear fit to the data.

IV. Grease thickness and comparison with simulation results

At first it is most interesting to investigate the dependence of R_{thjh} on the thickness of the thermal grease layer. This is done by introducing successively thin metal spacer stripes between heat sink and module at the edges of the module. Investigated was a 10A Easy1B PACK module FS10R06WE3 by Infineon-eupec. It must be mentioned that not only the chip under test but also the surrounding dices were heated up at similar power levels to take proximity effects into account and to measure a thermal resistance value characteristic for the application situation.

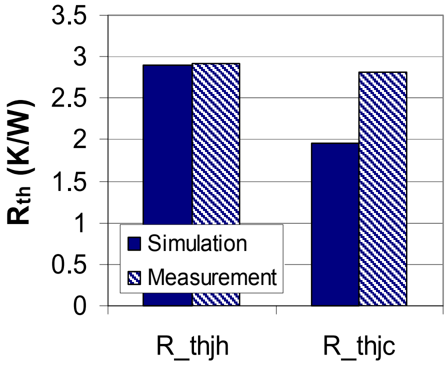

Fig. 8: Simulated and measured R_{thjh} (left) and simulated and extrapolated R_{thjc} (right). The extrapolation is obtained from Fig. 7 as the intersection at d_{grease} = 0 µm. Note that simulated and extrapolated R_{thjc} do not fit to each others.

Fig. 7 reveals that the thermal resistance R_{thjh} depends nicely linearly on the thickness of the grease layer. Without spacer stripes the thickness of the grease layer amounted to 13 µm. This value is quite characteristic for EasyPIM^{TM} and PACK modules delivered by Infineon-eupec. We typically find a grease thickness around d ≈ 20 µm, proving that the module construction ensures a good thermal contact between module and heat sink. Using an experiment as the one shown in Fig. 7, all measurements may be interpolated to a common grease thickness. This simplifies the quantitative comparison of different modules and enables more quantitative technological comparisons.

It might be concluded that the intersection with the R_{th} axis in Fig. 7 at d_{grease} = 0 µm yields the junction to case thermal resistance. However, R_{thjc} may also be obtained from finite element simulations quite accurately. Performing such a simulation (Fig. 9) on a FP10R06WE3 module, for example, yields a value of roughly R_{thjc} = 2.0 K/W differing significantly from the value of 2.8 K/W extrapolated from the measurement. We conclude that besides of the volume thermal resistance of the grease a thermal contact resistance also has to be taken into account. This also explains why the measured R_{thjh} corresponds to a simulation using 50 µm of thermal grease thickness instead of the measured value of 20 µm. Using this condition measured and simulated data yield good coincidence as shown in Fig. 9. We conclude that the additional 30 µm simply represent the thermal contact resistance in the simulation.

Another explanation could be that the thermal conductivity of the grease layer depends on its thickness. In that case we would expect a non linear dependence of R_{thjh} on d_{grease}, however (cp. Fig 7).

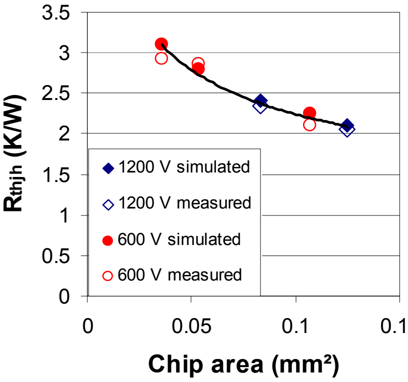

Fig. 9: Comparison of simulated (closed symbols) and measured (open symbols) R_{thjh}. The straight line is a guide to the eye. All simulations were done using a grease thickness of 50 µm. with λ = 1K/Wm.

V. Proximity effect

It has been pointed out in the above paragraph that not only the die under test but also the surrounding dices have been actively heated during the experiment. The main reason is that the R_{thjh} of the chips might not be decoupled. In case of modules without base plate the thin bottom copper layer allows only a limited heat spreading on top of the thermal grease.

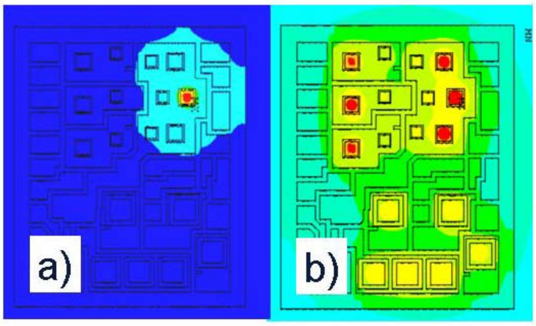

Fig. 10: Finite element simulation of a FP10R06WE3 module. a) Thermal top view with only one IGBT being powered. b) Simulation under a typical 100% load driving conditions. Details see text.

This may also easily be derived from Fig. 10 where a top view of a thermal finite element simulation of a FP10R06WE3 module can be seen. Part a) shows the result when only a single IGBT is powered. The heat clearly spreads out over a distance exceeding the next neighbour chip positions. Part b) shows a thermal simulation for a typical 100% load condition, i.e. an inverter running at 100% driving mode (cos ϕ = 0.8). Here, the chips are clearly thermally coupled. The condition shown in b) was used for all simulations shown in Fig. 8 and 9. The measurements mentioned in Fig. 7-9 were performed by powering all neighbouring IGBTs.

It can be concluded that each chip may only use a limited DCB area for cooling. In contrast to modules with base plate the specification of a case to heat sink thermal resistance for the module as a whole unity therefore does not make any sense.

To obtain a figure of the thermal coupling length a simulation approach is shown in Fig. 11. Here the DCB-area available for a single chip has been varied. In the radial symmetric simulation the distance between chip edge and DCB-edge is varied and the resulting R_{th} values are calculated. Note that this approach corresponds to periodic boundary conditions, i.e. also yields the results for equidistantly placed chips dissipating all the same power losses within a module.

Two conclusions may be derived from Fig. 11: First, the junction to case thermal resistance is

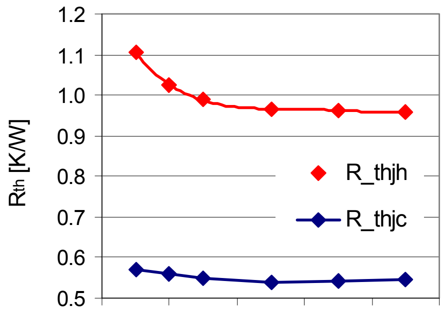

Fig. 11: Simulation of thermal coupling in DCB-modules without base plate. Here, a single 42 mm² chip has been investigated and the DCB area available for cooling has been varied. Plotted is the thermal resistance as a function of the distance between chip edge and DCB edge.

quite well defined and almost independent from the DCB size. Secondly, the junction to heat sink resistance decreases approximately until the chip edge - DCB edge distance amounts to 4 mm and is constant for values larger than this. Consequently, chips in a base plate less module may be regarded as thermally decoupled if their edge to edge distance amount to more than 8 mm and a proximity effect has to be taken into account for distances less than that.

Since both volume and cost issues drive the development of modern power semiconductor modules to more and more compact designs this is an important issue for determining the datasheet thermal resistances.

R_{thjH} (K/W)	Decoupled: Single IGBT powered	Coupled: All IGBTs powered	Deviation (K/W)
Simulation	2.7	3.1	+0.4
Measurement	2.4	2.9	+0.5

Table 1: Comparison of coupled and decoupled R_{th}-values for a FP10R06WE3 Easy1B-module.

Table 1 compares the measured and simulated results: It can clearly be seen that R_{thjc} depends on the operation conditions! It is significantly reduced when only the die under test is heated up. To take this proximity effect into consideration, only the worst case thermal resistances under parallel operation of all dices are given in eupec's data sheet of the module. It is important to note, however, that this approach or R_{th} definition is not standardised and care must be taken when datasheet values of different suppliers are compared.

VI. Mounting process

A third experiment enabled by the new set-up is the direct observation of the module mounting process. When a module is mounted a force is applied between module and heat sink. Excessive thermal grease between module and heat sink will be pressed out as long as such force is present. Especially for a module without stabilising base plate the force must not be too strong to ensure that no DCB cracks are induced! Infineon's-eupec's solution for a reliable mounting of base plate less modules with limited forces is the use of mounting clamps for the easy module family (see Fig. 12).

Fig. 12: Easy 1B: The new compact member of Infineon's-eupec's Easy module family of modules without base plate. The metal mounting clamps are directly moulded into the housing.

In contrast to the direct fixing of the module with a screw these clamps ensure that a defined force on the module is present also after the mounting process which takes only a few seconds. But how long does the settling process by pressing out excessive thermal grease really take? The new set-up presented here has allowed a quantitative measurement:

Fig. 13 shows that the settling of an easy1B module when directly pressed onto the heat sink with the clamping force of 70 N takes up to 40 seconds! Of course this result depends on the amount of grease dispensed and on the grease's viscosity. Consequently, for modules without base plate without the clamp mount technology the mounting screws should either be retight-

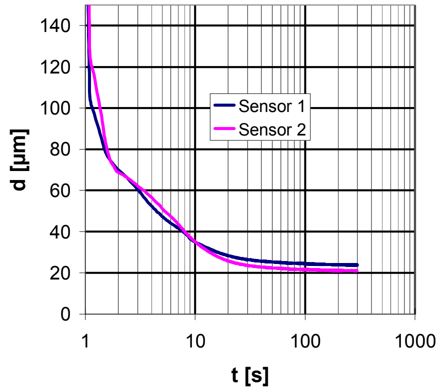

Fig. 13: In situ observed settling of an Easy1B module after fast mounting at t ≈ 1 s. The two curves show the module to heat sink grease thickness measured at the two sensor positions. Note the logarithmic time scale. After approx. 40 s a value of 20 µm is approached.

ened after some time or it must be assured that the amount of grease dispensed is very small and well controlled to assure that only a minor amount has to be pressed out. We conclude that the clamp mount technology provides a very tolerant and reliable mounting solution.

VII. Load cycles and long term behaviour.

After having investigated the mounting process it is most interesting to look at the longer term effects as well. In Fig. 14 the thermal grease thickness at the two sensors for a time scale up to approx. 17 ½ h is shown. Within this period of time several load cycles with 30 s periodicity at the rated current for all IGBTs are driven. The current (and therefore thermal) load seems to increase the grease thickness by 1-2 µm at each cycle. From calibration measurements, however, we know that a similar effect occurs through the heating of the measured copper plane which has an effect on the eddy currents as a consequence of the thermal resistance change. Hence, it cannot be excluded that the observed effect is a measurement artefact. On the other hand Fig. 14 clearly reveals that small long term changes in the thermal grease thickness are present and amount to several µm. Thus, also under the aspect of long term reliability the clamping technology ensures through constant forces that the module – heat sink thermal contact is always formed in an ideal way.

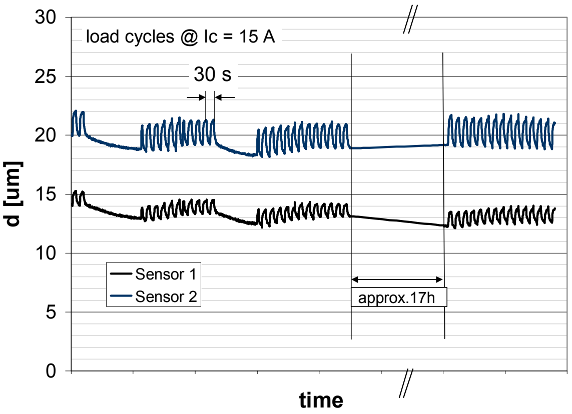

Fig. 14: Long term development of the thermal grease thickness measured for an Easy1B module. Note that the ripples during 30s power cycling might be a measurement artefact. A long term settling process of several µm is observed and also under operation conditions changes of several µm can be observed.

The ability of measuring both, R_{th} and grease thickness simultaneously enables us to investigate application relevant long term effects in detail and is a prerequisite for upcoming further studies.

Summary

We have introduced a newly developed experimental set-up capable of measuring both thermal resistance and thermal grease thickness. The placement of the thermocouple within the heat sink has been shown to be crucial for obtaining accurate results. From a thermal grease thickness series and comparison of experiment and simulation it has been derived that a thermal contact resistance exists which contributes significantly to the case – heat sink thermal interface.

For thermal measurements on modules without base plate it has been shown that a) each chip may only use a limited DCB area for cooling and b) proximity effects have to be taken into account when the chip to chip distance is less than 8 mm.

Finally, the usefulness of mounting clamps for modules without base plate has been demonstrated and the settling of a module after mounting has been measured in situ.

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