THERMAL MANAGEMENT CONCEPTS FOR POWER ELECTRONIC MODULES

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ABSTRACT

The amount of electronics in vehicles of any kind increases steadily, for each new generation more functions, previously realized mechanically, are solved electronically, simultaneously completely new application-areas are invented that demand electronics too. The growth happen in the control electronics as well as in the power electronics areas: from advanced motor-controllers to power electronics in electric power steering, electrical braking, advanced fan drives, electrical turbo generators, piezoelectric valve controllers and of course starter generator designs. A three dimensional thermal finite element (3DFE) simulator and a thermal camera have been used to investigate the thermal heat distribution in a power module. The heat distribution in a MOSFET-module with and without a Cu-baseplate, working as a heat spreader has been studied.

I. INTRODUCTION

Thermal impedance and heat distribution in such dense assemblies does not only effect the device characteristics but also the reliability and lifetime of the module. Usually the geometry for a power module is defined by the mechanical design. Therefore an accurate thermal and electrical design is required to optimise layout and wire bonding within the given geometry.

The power module killer above them all is the simple variation of temperature, such as daily temperature variations in the environment and temperature cycles occurring inside the power modules during operation. The reason is that the power modules constitute an assembly of different materials having quite different physical properties. A sandwich of dissimilar materials, such as copper and ceramics or aluminum and silicon, will experience stresses and strains during temperature variations due to differences in the coefficient of thermal expansion (CTE) between the materials. These stresses and strains will inevitably cause fatigue cracking and delamination of sandwiched materials, they literally fall apart, as the temperature varies and the power modules will die. The larger the temperature swings the larger the stresses and strains; the more cycles that occur the worse. We need to understand how the sizes and numbers of different temperature cycles influence the integrity of the material-sandwiches.

II. TECHNOLOGY OF TODAY

The amount of silicon, especially in power modules, is increasing dramatically. To give an example: An integrated MOSFET-module for a typical electrical power steering application in a SUV is using at least 180 mm² of silicon and even more depending on the power requested; in comparison a Pentium4 microprocessor manufactured by the latest process technologies from Intel uses 150mm^2 of silicon.

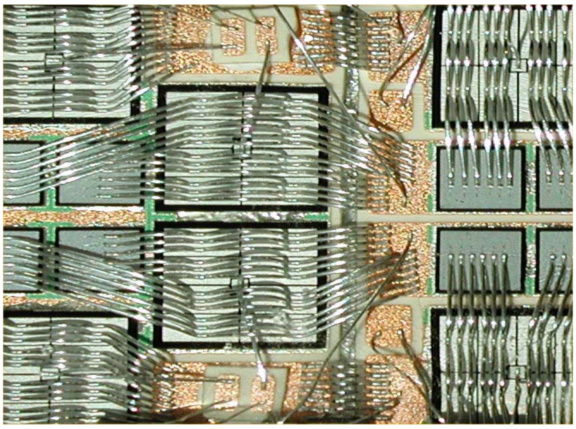

Figure 1. Extreme power density in perfection: Wire bond layout for an IGBT – module for electrical traction

Theoretically fractal object are infinitesimally sub-divisible in this way; each sub-set; however small, containing no less detail than the complete set, basically fractal dimension measures result and discussions. Several methods for estimating the fractal dimension of complex surfaces have been proposed. This work was performed by using capacity, correlation and information dimension methods. The increased amount of power electronics is followed by demands regarding size and cost: more power and less space leads to rapidly increasing power densities and the cost driver tends to reduce the amount of silicon that the designer is allowed to use, which again leads to increased power densities, because there is less space available for more heat dissipation. One solution to this typical dilemma is: take smaller dies and spread the heat as much as possible. Consequently the engineers do not apply organic circuitry substrates (like epoxy boards (e.g. FR4)) as a thermal basis for the dies. They go for more exotic solutions like ceramic substrates, e.g. DBC (Direct Bonded Copper,) as a platform for power semiconductors and a strong copper baseplate to spread the heat before the heat is conducted to a system heat sink (typically aluminium).

When characterizing the thermal behaviour of a power module the concept “thermal stack” is a strong tool. The thermal stack defines the material composition and the geometries of the individual layers that the heat has to travel through on the journey from the junction of the power chip to the outside world.

A power module can be realised in several ways, below three typical examples:

1. As discrete components (e.g. TO220’s) that are mounted using screws.
2. Bare silicon chips on a DBC substrate that is glued to the aluminium heat sink.
3. Bare silicon chips on a DBC substrate, which again is soldered onto a copper baseplate, which then is torque, mounted to the aluminium heatsink.

It is seen, that the discrete solution using TO220’s offer approximately the same thermal performance as the bare-die-on-DBC-glue. The TO220 solution features extremely high heat spreading within the package itself due to the large copper lead frame, but the solution is punished by the electrical insulation layer between the component and the heat sink. The bare die solutions offer much more compact solutions than the discrete one, so the best solution taking all considerations into account clearly is the bare-die-on-DBC where the DBC is soldered onto a copper baseplate. The thermal stack with copper baseplate should be soldered void free to provide an optimum of thermal and electrical conductivity. To meet not only technical demands but also an environmental friendly solution the solder layer should consist of a lead-free solder alloy. This was a real challenge for process engineers because a real void free wetting required lead. A sophisticated vacuum soldering process now guarantees both: solid and void free soldering without any lead in the solder joint of Chip-to-DBC and DBC-to-baseplate. Process optimisation now allows even simultaneous soldering of Chip-to-DBC and DBC-to-baseplate in one step. So competitive costs and best thermal properties are combined in the thermal stack building process.

Material	k [1]	Layer thickness [mm]		
		TO220	Glue	Basepl.
Silicon	150	0.175	0.175	0.175
Solder	55	0.1	0.1	0.1
Copper	390	1	0.3	0.3
Al_2O_3	24		0.380	0.38
Copper	390		0.3	0.3
Solder	55			0.15
Copper baseplate	390			3
Interface [2]	1	0.2	0.1 [3]	0.1
Al heat sink	200	5	5	5

Figure 2. Material properties of a power module stack

Material	$R_{th\ junction\ to\ ambient}$ [K/W]		
	TO220	Glue	Base-plate
Silicon	2.38	2.50	1.45
Solder			
Copper			
Al_2O_3			
Copper			
Solder			
Copper baseplate			
Interface			
Al heat sink			

Figure 3. Thermal Resistance of a power module stack

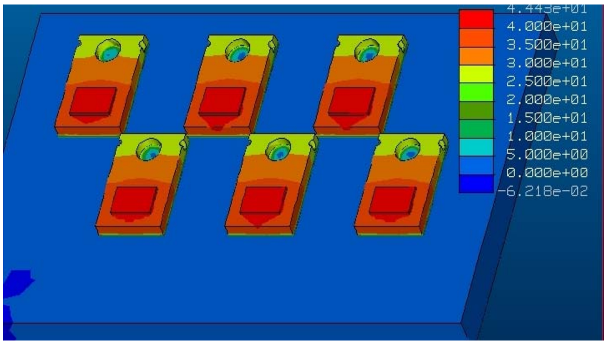

Figure 4. TO220's mounted on a heat sink using an electrical insulator, Rth = 2.38K/W

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[1] Thermal conductivity. [W/(m K)]

[2] The discrete component needs an electrical insulator as interface material thus the larger thickness than for the two other examples that only need the thermal conductivity. In the latter cases, the electrical insulation is established in the ceramic layer (Al_2O_3).

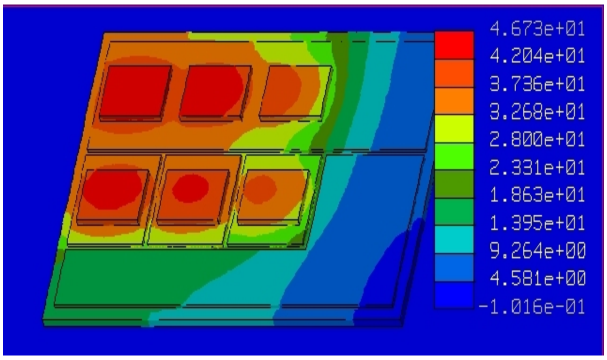

Figure 5. Bare die on DBC, glued to the heat sink, Rth = 2.5 K/W

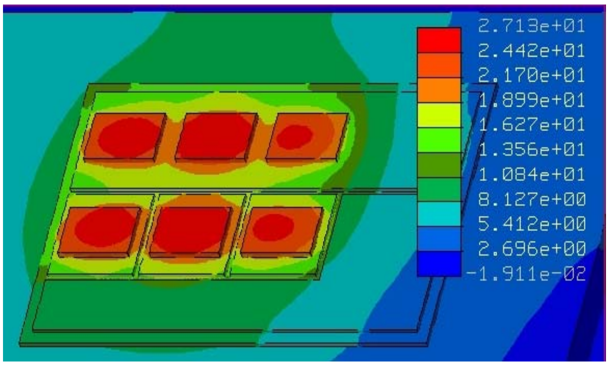

Figure 6. Bare die on DBC which is soldered onto a copper baseplate

Figure 7.and Figure 8. illustrates the comparison of simulation against measurement of a chip in a module.

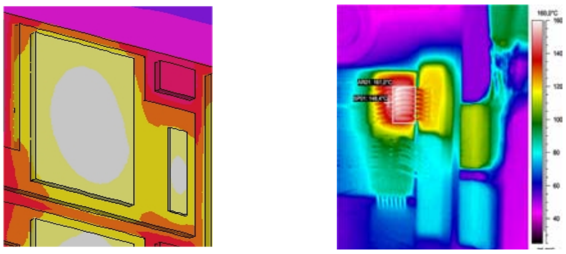

Figure 8. Simulation (left picture) –Tjmax. :157,8°C and measurement -Tjmax. : 148,4°C without baseplate

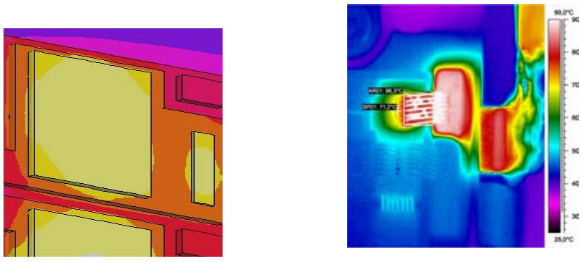

Figure 9. Simulation –Tjmax. :80,9°C, measurement-Tjmax : 71,2°C with baseplate

III. FUTURE TECHNOLOGY "LIQUID COOLING"

Liquid cooling of power electronics has been utilised for many years, in some segments more than others. The acceptance for applying liquid cooling varies from business segment to business segment: the automotive industry for example has always used liquid cooling for cooling the combustion engines, so the idea of cooling power electronics in an automotive application is not frightening for the design engineers.

In other segments, the idea of having water flowing through power electronic assemblies is most disturbing. Maybe the biggest impediment for applying liquid cooling has been the relative high cost and the limitations in performance that confines the usability to more exotic applications where no alternative exists - these limitations being large temperature gradients across the cooling areas and high pressure drops in the coolers that make large/expensive pump systems necessary.

Standard liquid cooled power modules suffer from two major drawbacks: 1: high cost and 2: inhomogeneous cooling.

1: Standard liquid cooled power modules feature copper baseplates with quite complicated structures e.g. pin fins, which are necessary in order to achieve sufficient cooling. And structuring costs: a typical baseplate for a large module gets five times more expensive with pin fins compared to the flat baseplate. The figure below shows an

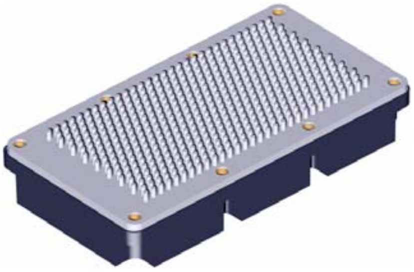

Figure 10. Standard pin fin cooler with circular pins.

2: The other major disadvantage using standard liquid cooling is the inherent temperature gradient, which arises through the module due to the warming up of the coolant, see Figure 2. The blue arrow indicates the flow direction of the coolant.

In order to reduce cost and to improve the cooling performance, a cooling system has been developed that solves both problems:

Cost is reduced since standard flat baseplate modules can be cooled while the cooling is highly effective and homogeneous or even tailored, across the baseplate.

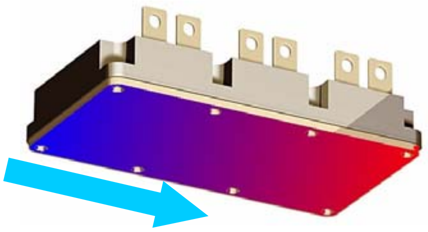

Figure 11. Temperature gradient through the module.

The fundamental idea is to cool perpendicular instead of parallel to the surface and to drain the coolant before it heats up and starts creating gradients in the baseplate. Thus the name: “Shower Power”.

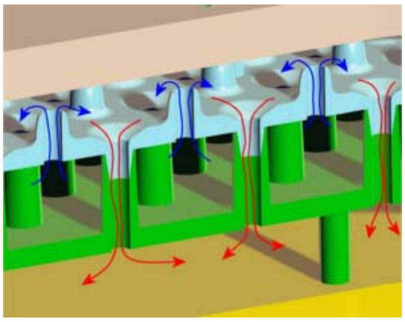

Figure 12. Perpendicular cooling.

Figure 12. Shows this basic idea: the liquid is sprayed onto the baseplate and led away right away; all the inlet nozzles injects liquid with the same temperature and the liquid is removed before creating temperature gradients in the baseplate. A further dramatic improvement of the cooling efficiency is achieved by reducing the number of inlet and outlet nozzles, thus increasing the flow velocities.

The second fundamental idea is to connect these inlet and outlet nozzles with a channel that constantly changes direction: a meandering structure. Figure 13. shows an example.

The red arrow in the figure indicates the flow path of the coolant. This brings forth a high cooling efficiency because the liquid is mixed every time it changes direction, thus transporting heat away from the hot module surface. Now, these meandering channels, or unit cells, are to be feed in a parallel fashion, maintaining the original parallel injection concept, this is achieved by incorporating a finger-like structure on the backside of the part, see Figure 14.

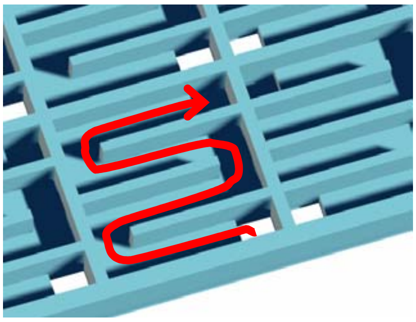

Figure 13. Meandering channel unit cell.

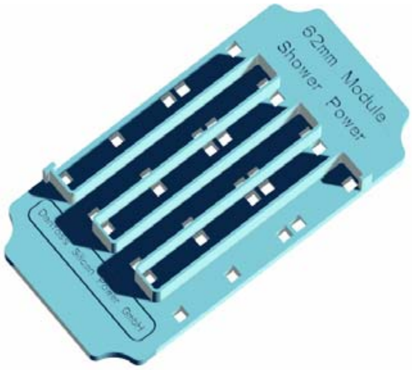

Figure 14. Finger-structure on backside.

The fingers interlock so that one finger supplies coolant while the neighbouring finger drains coolant. The arrangement is symmetric in a manor that assures that all unit cells have the same pressure drop, and thereby the same cooling effect, i.e. true parallel cooling.

Another advantage of the new cooling system is the small pressure drop, which is a consequence of the laminar flow conditions that occurs due to the small channel dimensions (a few square mm cross section).

A simple plastic part has been designed, which incorporates all the features mentioned above: parallel fed meandering cooling cells, which cools the flat module baseplate very efficiently at a low cost. The channel geometry, e.g. number of bends per unit cell, length and cross-sectional area of the channels has been optimised using powerful CFD tools (computational fluid dynamics).

Practical demands, such as minimising the risk of clogging due to particles in the coolant have been considered, also bubbles, that are inevitable formed in the cooling system, are to be flushed out easily independently of the orientation of the cooling system (i.e. upside down). Typical channel sizes are 2.5-3mm wide having a square cross section.

The figure below shows an example of a large power module, suitable for a traction application, having a flat baseplate, being liquid cooled using the Shower Power principle. The key-part is the blue Shower Power plastic part.

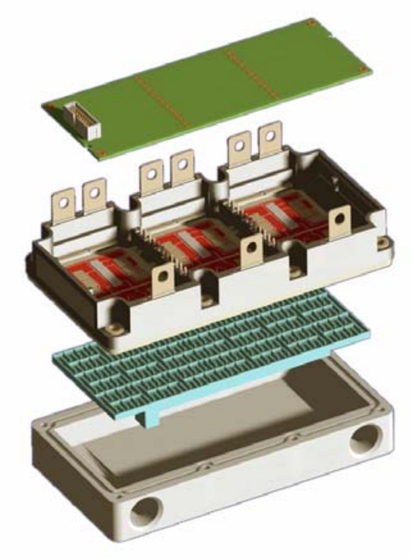

Figure 15. Exploded view of a large liquid cooled power module.

Practical tests have shown, that the cooling effect achievable using Shower Power is very high: the heat transfer coefficient has been measured in different versions of the design, and values were found of h>12.500 W/(m^{2}K) @10liters per minute ethylene-glycol/water (50%/50%): The figure below compares the cooling efficiency for Shower Power with a standard pin fin cooler.

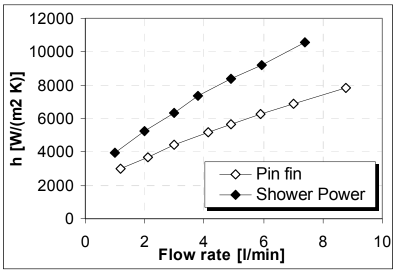

Figure 16. Heat transfer coefficient vs. flow rate.

The Shower Power cooler is seen to be 25-30% more efficient than the pin fin cooler. The corresponding pressure drops at 8l/min was found to be 125mbar and 25mbar respectively for the Shower Power and the pin fin cooler.

The homogeneity of the cooling effect of a Shower Power cooled module has been measured, using thermo vision, and compared with a standard pin fin cooler module. The chart below shows the result.

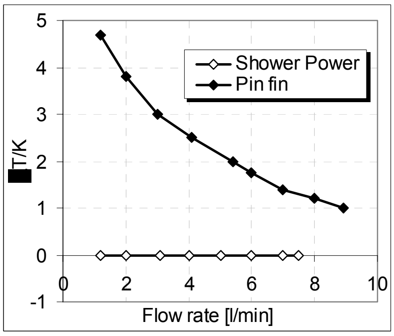

Figure 17. Comparing homogeneity of the cooling effect.

It is not possible to detect any temperature gradient across the baseplate in the Shower Power case, whereas the temperature gradient in the pin fin case ranges from 1-5K. At lower flow rates the gradient increases rapidly for the pin fin cooler, while the Shower Power cooler gets equally hotter everywhere.

It is even possible to tailor the cooling if the power module has hot spots, e.g. semiconductors running especially hot, the channel geometry underneath the hotspot is simply made narrower in order to increase flow velocity and hence the cooling efficiency.

Using standard cooling principles, paralleling more modules can be tricky in that temperature differences between the individual modules increase the risk of thermal runaway.
The shower power principle can easily be expanded to accommodate as many modules as one needs, the figure below shows an assembly for six 62mm standard modules.

Figure 18. Six-pack arrangement.

All the individual modules are cooled equally efficiently; the backside of the cooler part simply repeats the interlocking finger principle on a larger scale, so that all unit cells underneath all the modules are feed with the same coolant temperature.

In critical applications, it can be advantageous to design out the large copper baseplate, thus cooling the DCB substrates of the power module directly; the figure below shows an example.

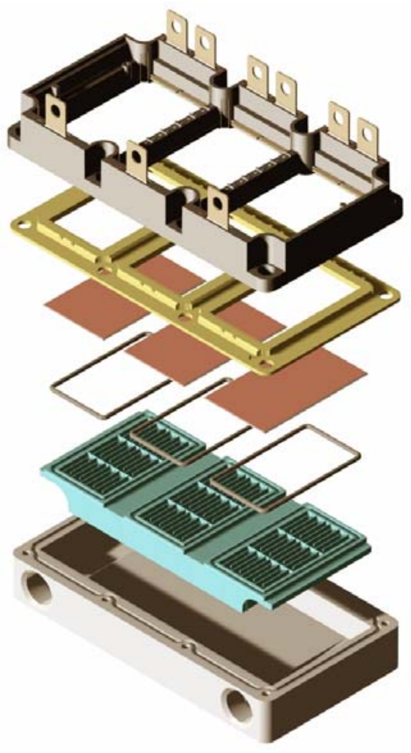

Figure 19. Direct liquid cooling of DCB substrates.

The individual substrates are again cooled equally effectively using the same principle as above for cooling several modules in parallel.

V. CONCLUSION

Different cooling system simulations have been performed. The measured temperature has been compared with the corresponding calculations. According to the Boundary Conditions all cooling system can be used for power electronic module. The design of the ShowerPower coolers presented above have all been open coolers, where the devices to be cooled have been cooled directly on their backsides. Of course the concept is not limited to open coolers; a lid is easily applied making the concept suitable for high-pressure applications as well, where direct cooling of the standard power module might lead to failure due to excessive bulging from the high pressure.

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