Cost Effective Direct-Substrate Jet Impingement Cooling Concept for Power Application

Bassem Mouawad, University of Nottingham, UK, bassem.mouawad@nottingham.ac.uk
Robert Abebe, University of Nottingham, UK
Robert Skuriat, University of Nottingham, UK
Jianfeng Li, University of Nottingham, UK
Liliana De Lillo, University of Nottingham, UK
Lee Empringham, University of Nottingham, UK
C. Mark Johnson, University of Nottingham, UK
Andy Roberts, RAM Innovations Ltd, UK
Robert Clarke, RAM Innovations Ltd, UK
Geoff Haynes, Inspirit Ventures, UK

Abstract

Direct substrate jet impingement cooling can eliminate the use of the baseplate and significantly reduce the weight and volume of conventional thermal management solutions. This work demonstrates a cost-effective manufacturing approach based on printed circuit board technology to create impingement cells under a direct bonded copper substrate. Results from both computational fluid dynamics simulations and transient thermal tests verify the good performance of such jet impingement cooling systems under high power density conditions. Further work is ongoing to apply the present cooling and manufacturing technologies for the development of a range of high performance power electronic systems.

1. Introduction

In a typical power electronic module, the heat generated by the devices is removed by means of a conduction path through the substrate tile followed by the copper baseplate to the final fluid swept surface at which convection occurs. The baseplate is mounted onto a cooler in the form of a coldplate using a thermal conducting paste. In this case there are typically nine thermal interfaces between the die junction (where heat is generated) and the coolant fluid [1]. Previous work on jet impingement cooling for power electronics by the authors indicated that a metal heatspreader plate does not need to be included in the electronic package if a cooling system providing a sufficiently high heat transfer coefficient is used [2][3]. These direct coolers were relatively complex being fabricated from multiple metal parts that must be sealed to one another and to the cooled substrate. In other work, 3D printing was used to create the cooler, using either metal or plastic. Although this reduces the number of parts required, the process is relatively slow and there are remaining challenges associated with the sealing of the cooler to the substrate and the porosity of some laser-sintered materials. Here we report on the application of industry standard PCB assembly methods to realise an impingement cooler integrated with a DBC substrate as part of a single process flow. The resulting cooler offers a cost-effective, high-volume-capable, light-weight, compact, integrated cooling concept for power electronics and other high power density applications.

2. Integrated direct cooling jet impingement design

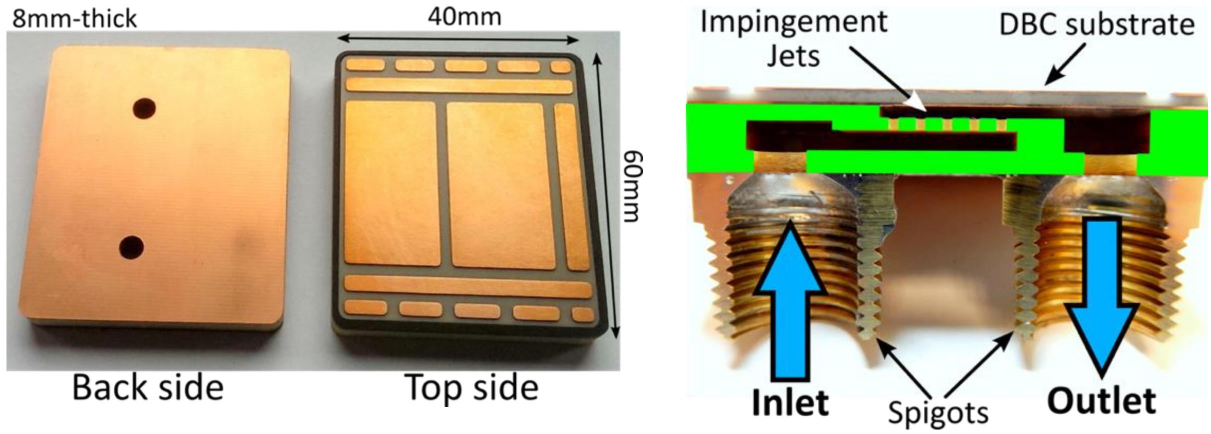

Fig. 1: Image of the integrated cooler (left) with a DBC substrate on top and holes that correspond to the inlet and outlet of the coolant at the backside and a cross-section image of the integrated cooler (right) showing the impingement jets.

In direct cooling of power electronics, the coolant fluid is in direct contact with the underside of the DBC substrate tile. There are a number of advantages found by cooling the underside of the substrate tile directly: 1) The removal of the baseplate in the package results in a shorter thermal path and therefore a lower thermal resistance between the power electronics and the coolant fluid; 2) The overall package can be made smaller with a reduced weight; 3) Fewer thermal layers in the package results in fewer interfaces between materials with different coefficients of thermal expansion (CTE); 4) The reduced mechanical stresses induced by differences in CTE improves the reliability of the package.

In this work, a direct-substrate jet impingement integrated cooler is presented. The cooler uses existing PCB manufacturing technology to create impingement cells within the laminates that are directly embedded with a DBC substrate. Fig. 1 shows the DBC substrate on top and the inlet/outlet channel on the backside of the embedded cooler. The cross-sectional image of the integrated cooler shows the coolant path which goes through the inlet, is sprayed on the backside of the DBC through the impingement jets, and is drained out of the package through the outlet.

In order to study the thermal performance of the cooler, a Silicon (Si) diode of 13mmx13mm was used as a heating source (see Fig. 2). The diode was mounted on top of the DBC substrate and located directly over the impingement jets. A flex PCB was soldered on the top of the diode to provide the interconnection. Power terminals were soldered onto the DBC substrate for electrical

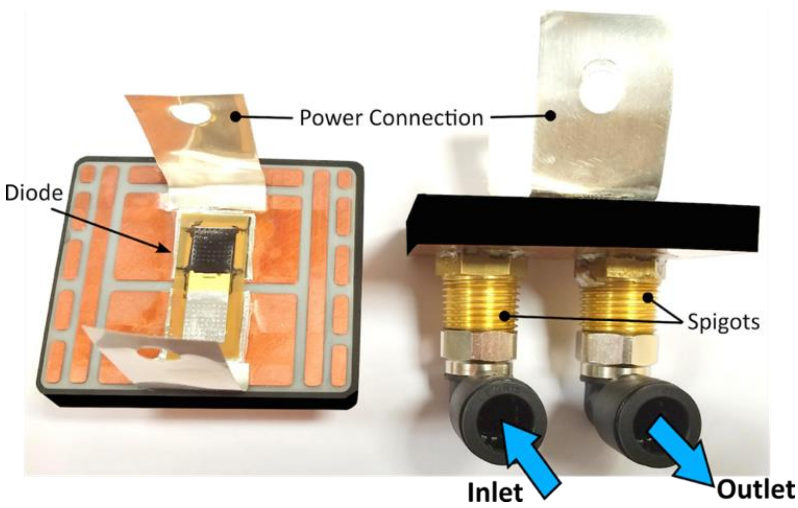

Fig. 2: Image (left) show the integrated cooler with a Si Diode mounted on top of the DBC substrate (on top of the impingement jets) and sprayed in black to measure the temperature with an IR camera. The image on the right shows the inlet and outlet channels.

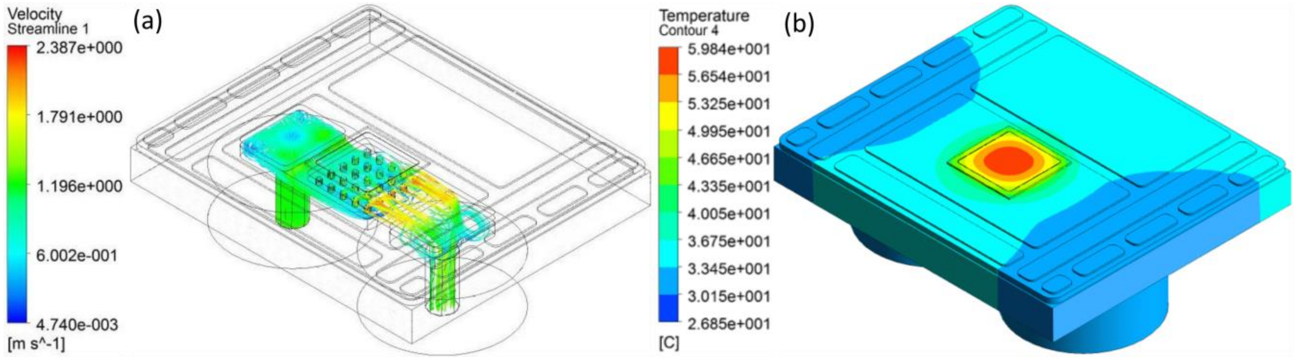

Fig. 3: CFD analysis show the velocity profile of the coolant in (a) and the simulated temperature profile in (b) with a calculated junction temperature of 60°C. The boundary conditions were set at a 172 W loss generation for the diode and the coolant flowing through the cooler at a flow rate of 1.51 l/min.

connection. A high emissivity coating was applied to the diode top surface to simplify temperature measurement using an IR camera.

3. CFD Analysis

ANSYS software was used to perform Computational Fluid Dynamic (CFD) analysis in order to investigate the thermal behaviour of the cooler and calculate the velocities and the pressure drop of the coolant at different flowrates. The internal heat generation set for the Si diode was based on a loss generation of 172 W, equivalent to a heat flux of approximately 1 W/mm^2. The coolant temperature at the inlet was set at 20°C and the flow rate was varied from 0.4 l/min to 1.51 l/min. Using ANSYS Fluent, a steady state thermal analysis was performed incorporating viscosity, energy and turbulence models. These models were set up to obtain temperature and pressure drop results.

Fig. 3 shows the velocity profile of the coolant and the temperature distribution at 172 W loss generation and flow rate of 1.51 l/min. It can be seen that at these boundary conditions, the junction temperature was calculated at 60ºC.

4. Experimental results

To evaluate the performance of the integrated direct-substrate, jet-impingement cooler, thermal impedance measurements were carried out on a Mentor Graphics Power Tester [4].

In order to validate the design and test the thermal performance of the integrated cooler at different

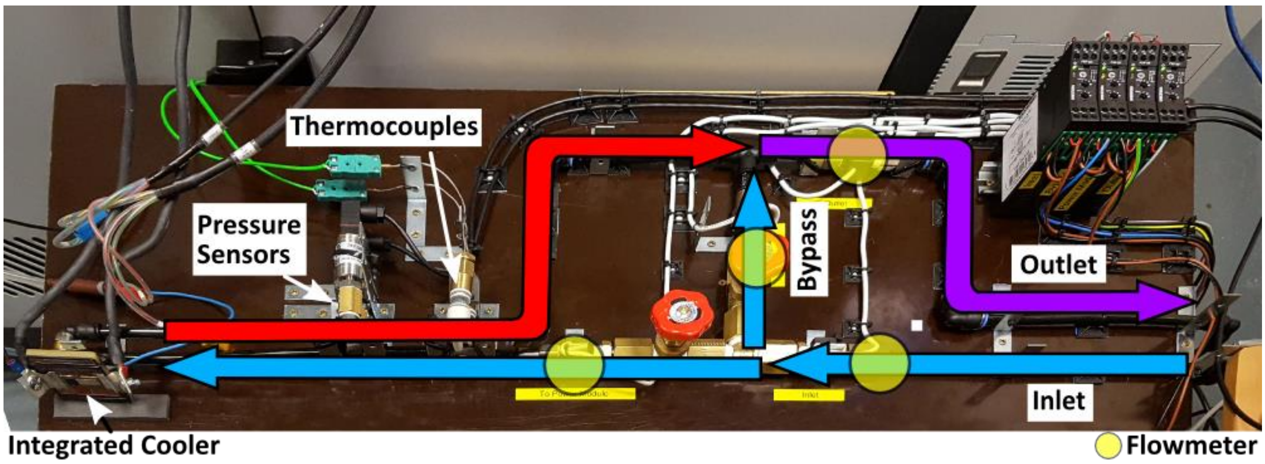

Fig. 4: Test rig for thermal impedance measurements with bypass system to regulate the flowrates through the integrated cooler, accommodating flowmeters, thermocouples and pressure sensors and connected to a chiller with DI water at 20°C. An IR camera (not shown here) was placed normal to the integrated cooler.

flow rates, a test rig was designed and constructed (see Fig. 4). This included the following components:

- A bypass system made to regulate the flow through the cooler
- Four flow-meters at the inlet, the outlet, the bypass channel and the integrated cooler
- Two thermocouples directly located and the inlet and the outlet of the integrated cooler
- Two pressure sensors to measure the pressure drop at the inlet and outlet of the integrated cooler

The junction temperature T_j of the Si diode was measured in two ways: directly with an IR camera set facing the integrated cooler, and indirectly using the relationship between the forward voltage at a small constant current and the junction temperature [5].

The transient thermal impedance measurements were acquired for different flow rates. A heating current of 90 A and a sensing current of 100 mA were applied to the Si diode. Table 1 lists the junction temperature measured using the electrical method, the thermal resistance of the structure and the pressure drop measured by the pressure sensors, of the integrated cooler at different flow rates.

Fig. 5 shows two thermal images acquired by the IR camera for two tests at 0.4 l/min and 1.51 l/min. The measured junction temperature was measured at about 100ºC and 63ºC respectively. This is in good agreement with the temperature measured using the electrical method (see Table 1). One should note that these results show a good agreement with the simulations for the same boundary conditions. For a flow rate of 1.51 l/min, the measured junction temperature was 63ºC compared to the simulated one which was equal to 60ºC (see Fig. 3).

Table 1 Results of Junction Temperature and thermal impedance and pressure drop at different flow rates

Test	Flow rate [l/min]	T_j [°C]	Zth [K/W]	deltaP [Bar]
A	0.4	101.1	0.479	0.016
B	0.47	95.7	0.445	0.019
C	0.5	93	0.428	0.02
D	0.71	78	0.337	0.032
E	0.85	72.4	0.304	0.041
F	0.94	70.4	0.292	0.047
G	1.03	68.7	0.282	0.056
H	1.21	66.3	0.269	0.073
I	1.38	64.7	0.259	0.09
J	1.46	64	0.255	0.099
K	1.51	63.2	0.251	0.106

Fig. 6 shows the differential structure function curves against the thermal resistance for all the tests listed in Table 1. The transient thermal analysis reflecting the measured junction temperature at different flow rates was also plotted. It can be seen that when the flow rate increases the junction temperature and the thermal resistance decreases.

The pumping power, proportional to the product of pressure drop and flow rate [3], is an important

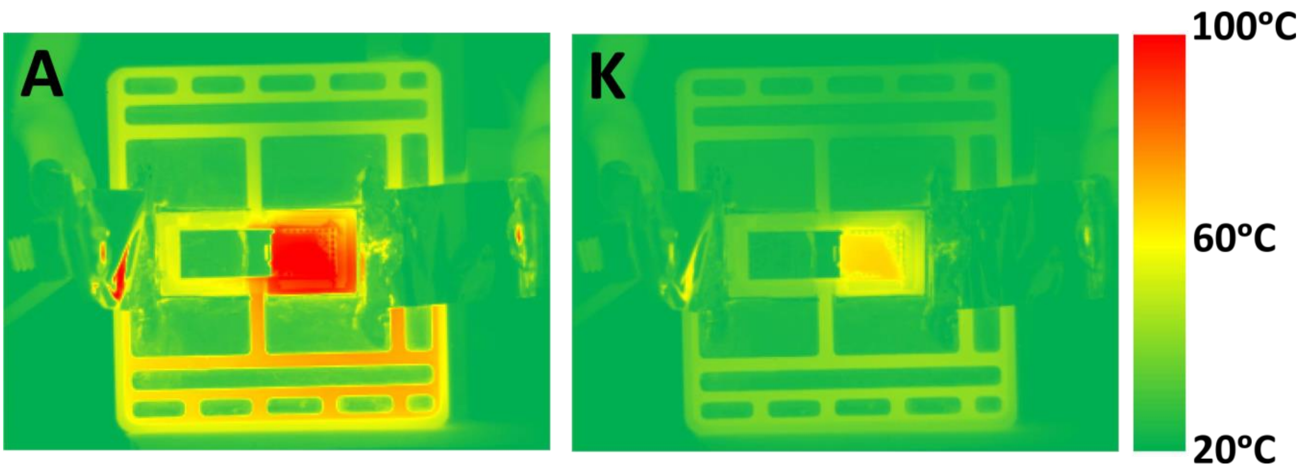

Fig. 5: Thermal images obtained with an IR camera showing the measured junction temperature of 100°C and 63°C with the coolant flowing through the cooler at a flow rate of 0.4 l/min and 1.51 l/min, respectively. The diode was dissipating 172 W and the coolant temperature was constant at 20°C.

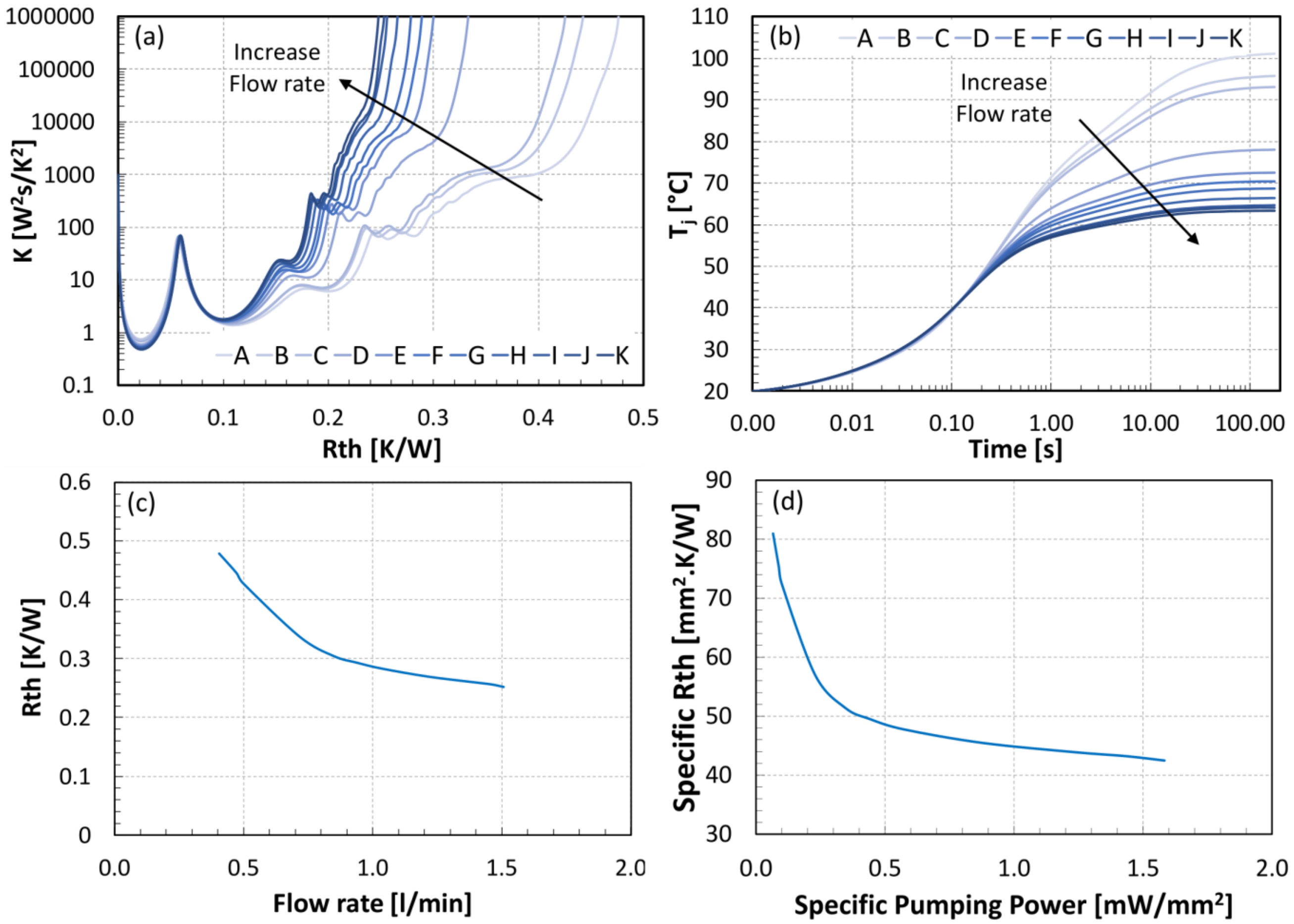

Fig. 6: (a) Differential structure function against the thermal resistance, (b) the measured junction temperature extracted from the transient thermal impedance measurements, (c) the measured thermal resistance of the integrated cooler at different flow rates. The plot in (d) shows the specific thermal resistance against the specific pumping power using the area of the Si diode (169 mm^2).

parameter since it determines the power that is required to pump (or to draw) a certain amount of fluid through the cooler. The junction to ambient specific thermal resistance was plotted against the specific pumping power. This shows that a specific thermal resistance of around 43 mm^2K/W was measured for a flow rate of 1.51 litres/minute and a specific pumping power of 1.5 mW/mm^2, a value that compares favourably with results obtained for the metal-based designs presented in [1].

These results show that the designed integrated direct substrate jet impingement cooler delivers excellent thermal performance by providing a high heat transfer coefficient at the cooled surface thus eliminating the need for a heat spreader plate as part of the assembly.

The peak junction temperatures can thus be significantly lowered, delivering a lower amplitude of thermal cycling for any load (power) cycling regime. This results in potential improvements in module reliability without having to resort to expensive base-plate/cooler combinations.

5. Conclusion

This paper has presented a cost-effective, light weight, ultra-compact direct-substrate jet-impingement cooling concept for power applications. A cost-effective, volume-capable manufacturing approach, based on printed circuit board technology, to create the impingement cells under a direct bonded copper substrate. Thermal studies show a very good correlation between CFD analysis and the experimental results. Measurements of the transient thermal impedance revealed a very low thermal resistance during the cooling transient at different flow rates. A Junction-to-Ambient Specific thermal resistance of around 43 mm^2K/W can be achieved at a flow rate of 1.51 litres/minute and a specific pumping power of just 1.5 mW/mm^2.

6. Acknowledgement

This work was part of the feasibility study program "Preparing for the Grand Challenge" supported by the Advanced Propulsion Center UK (APC UK).

7. References

[1] R. Skuriat and C. M. Johnson, "Direct Substrate Cooling of Power Electronics," in *13th European Conference on Power Electronics and Applications, (EPE)*, 2009, p. 4674–4683\r6311.

[2] C. M. Johnson, A. Castellazzi, R. Skuriat, P. Evans, J. Li, and P. Agyakwa, "Integrated High Power Modules," in *7th International Conference on Integrated Power Electronics Systems (CIPS)*, 2012, pp. 357–366.

[3] R. Skuriat and C. M. Johnson, "Thermal Performance of Baseplate and Direct Substrate Cooled Power Modules," in *4th IET Conference on Power Electronics, Machines and Drives (PEMD2008)*, 2008.

[4] M. Graphics, "Power tester 1500A—Lifetime testing and failure diagnosis of high-power semiconductors."

[5] U. Scheuermann and R. Schmidt, "Investigations on the VCE(T)-Method to Determine the Junction Temperature by Using the Chip Itself as Sensor," *PCIM, Power Electron. Intell. Motion, Power Qual. Nuremberg, Ger.*, vol. U. Scheuer, pp. 802–807, 2009.