Development and Demonstration of a Novel Immersion Two Phase Cooling High Power SiC Power Module

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***Abstract*—In this study, we propose a lead frame based half-bridge power module equipped with SiC power devices aimed for automotive applications. This suggested power module is directly integrated with the cooling chamber/enclosure, forming an immersion two phase cooling power module. unlike the commonly used power modules, which are constructed on standard direct bonded copper (DBC) substrates. For the power module demonstrated in this study, the DBC substrate is taken away and a dedicated copper lead frame is engaged to form the interconnections from the drain side. Moreover, the high loop bond-wire interconnections for the source/gate pads are abolished, and another piece of copper lead frame is utilized to form the interconnections from the source/gates side. Then, the lead frames assembled with the SiC MOSFETs are directly integrated with a cooling chamber to form an enclosure for filling with the dielectric coolant for direct immersion cooling. The power module developed and demonstrated in this study is with light weight and thin structure by withdrawing the DBC and bonding wires. Furthermore, the cooling efficiency of the developed power module is improved significantly by employing the direct device level immersion cooling technology. It comes about 60% of size reduction and 100% of heat dissipation capability improvement as compared with the regular Double-side-cooling (DSC) power modules.**

***Keywords*— power module: Immersion; two phase cooling; SiC chips; dielectric coolant.**

I. INTRODUCTION

After more than half century's evolution, silicon semiconductor material based power devices has approached its performance limits [1, 2]. While compared with the silicon material, wide-band-gap (WBG) semiconductor material, e.g. silicon carbide (SiC), possess the advantages of higher dielectric breakdown field strength (about 10x), higher electron saturation velocity (about 2x), higher energy bandgap (about 3x) and higher thermal conductivity (about 3x) [3]. Because of these supreme performance above the silicon material, SiC based power devices, which possesses higher operating voltage, larger current carrying capacity, higher operating frequency and higher operating temperature than the silicon based power devices, have been broadly employed in the 5G communications, automotive, aerospace, marine, energy and other industrial fields with raising demands for high voltage power transmission, energy saving and emission reduction [4,5]. However, SiC MOSFET based power modules possess higher output power and higher packaging density, which will result in higher consumption of electrical power and higher density of heat generation, sequentially it brings a big challenge to their thermal management and cooling solution design. Therefore, appropriate optimization of the thermal design and efficient cooling solution play a crucial function for developing the SiC MOSFET based power modules [6,7].

The illustrative configurations of the existing SiC power modules are presented in Fig. 1 for (a) DBC based power module with single-side-cooling (SSC)solution (b) DBC based power module with DSC solution, and (c) lead frame based power module with DSC solution. The common structure of a conventional power module is by attaching the SiC power chips to the DBC substrate, creating the interconnections from the drain side, and by bonding wires to the gate and source pads, constituting the interconnects at gate and source pad side. It is only capable to equip one cooling cold plate/heat sink at one side, producing the power module with SSC (refer to Fig. 1a). This type of conventional wire bonded SSC power module is with low cooling efficiency and thick package structure due to the thick substrate and high wire loop. To improve the cooling efficiency, players have made many efforts to develop the power module with DSC solution. The usual method to fabricate a typical DSC power module is to embed the SiC based power devices between two ceramic based substrates, producing a power module which is generally designated as a 'sandwich module' (refer to Fig 1b) [8]. However, the DSC power modules with "sandwich" structure are normally thick and with poor thermal performance because of the redundant DBC substrate. Recently, some research works have been focused on the DBC-less DSC power module [9, 10]. In this type of power module, the DBC substrate is eliminated and substituted by a dedicated copper lead frame, creating the interconnections from the drain side of the power devices. And another customized copper lead frame is bonded to the source/gate pads, establishing the interconnections from the source/gate side of the power devices (refer to Fig. 1c). This type of power module can be DSC with thin package structure. However, their thermal dissipation capability dramatically relies on the performance of the of thermal interface material (TIM). The junction to ambient thermal resistance may increase significantly for TIM with low thermal conductivity [11]. To avoid such limitation, we need to explore a power module fully integrated with the efficient thermal management solution.

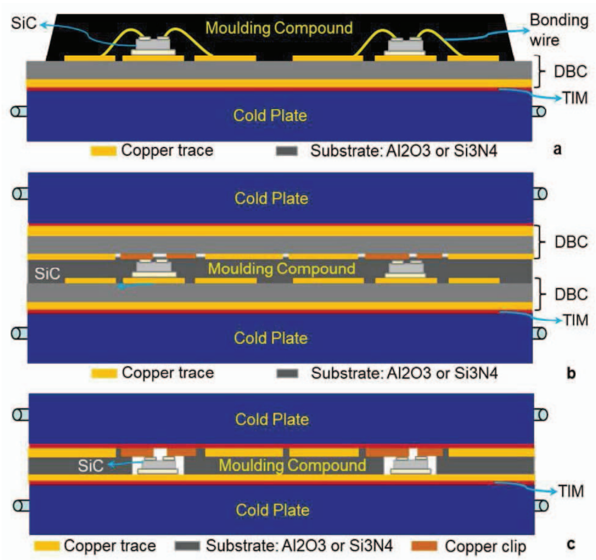


Fig. 1. Schematic configuration of the existing SiC power modules for (a) DBC based power module with SSC solution (b) DBC based power module with DSC solution, and (c) lead frame based power module with DSC solution

II. METHODOLOGY

In this study, a half-bridge power module equipped with SiC power devices aimed for automotive applications is proposed. The schematic configuration of the proposed immersion 2 phase cooling power module is shown in Fig. 2 for (a) 2D scheme, (b) 3D structure. As shown in the figure, the power module is directly integrated with cooling chamber/enclosure and forming an immersion two phase cooling power module. unlike the commonly used power modules, which are based on DBC substrates. For the power module demonstrated in this study, the DBC substrate is taken away and a dedicated copper lead frame is engaged to form the interconnections from the drain side. Moreover, the high loop bond-wire interconnections for the source/gate pads are abolished, and another piece of copper lead frame is utilized to form the interconnections from the source/gates side. Then, the lead frames assembled with the SiC MOSFETs are directly integrated with a cooling chamber to form an enclosure for filling with the dielectric coolant for direct immersion cooling. The power module developed and demonstrated in this study is with light weight and thin structure by withdrawing the DBC and bonding wires. Furthermore, their cooling efficiency is raised significantly by employing the direct device level immersion cooling technology for the power module.

To develop and demonstrate the proposed immersion 2-phase cooling power module, the following approaches are implemented. At first, the flow and thermal model are built for the fluid dynamics and heat transfer simulation. The flow field and thermal profile in the power module with different design variables are simulated and analyzed, and the necessary design parameters are optimized. After the parametric optimization and design finalization, the proposed immersion 2-phase power module is fabricated. Lastly, the fabricated power module is put into a test system for performance demonstration and characterization. The SiC chip junction temperature of the proposed power module at different power conditions is measured and the performance of the proposed immersion two-phase power module is evaluated.

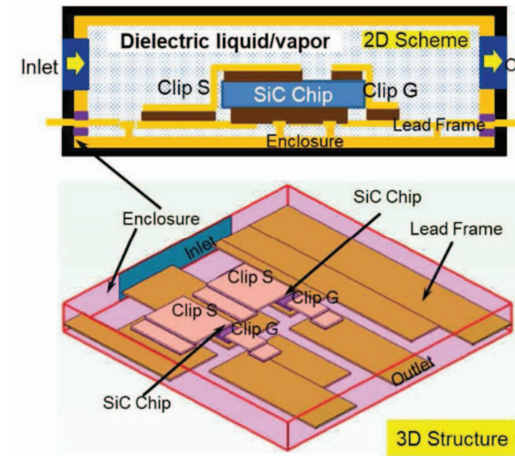


Fig. 2. Schematic configuration of the immersion two phase cooling power module propoded in this study for (a) 2D scheme , (b) 3D structure

III. THERMAL MODELING AND SIMULATION

Fluid flow and heat transfer model is built for the flow and heat transfer simulation. The design variables include the number of the inlets and outlets, the size of the inlets and outlets and the flowrate of the dielectric fluid flowed through the power module.

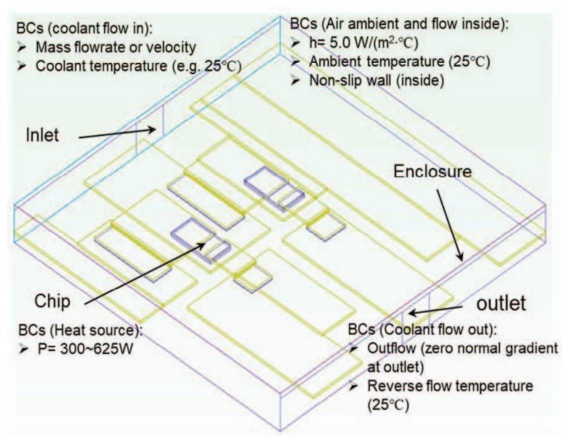


Fig. 3. Flow/thermal model and boundry conditions (BCs) for the flow field and heat transfer simulation

The simulation model and boundary conditions (BCs) are shown in Fig.3. It indicates that the heat power for each chip varies from 300W to 625W and the surrounding temperature outside chamber/enclosure is fixed at 25°C. The other conditions include the coolant temperature at the inlet, the volumetric flowrate at the inlet and the outflow condition at the outlet. The simulated temperature profile in the cooling enclosure of the immersion two phase cooling power module is shown in Fig. 4, which reveal that the junction temperature of chip-#1 and chip-#2 is similar (around 100°C), suggesting the good temperature uniformity between Chip-#1 and Chip-#2.

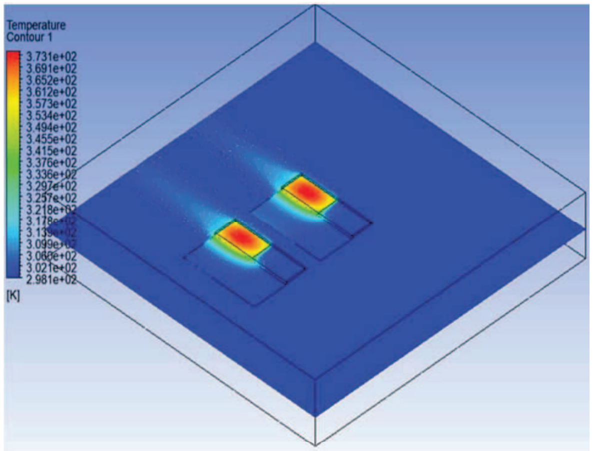


Fig. 4. The simulated temperature profile in the cooling enclosure of the proposed immersion two phase cooling power module

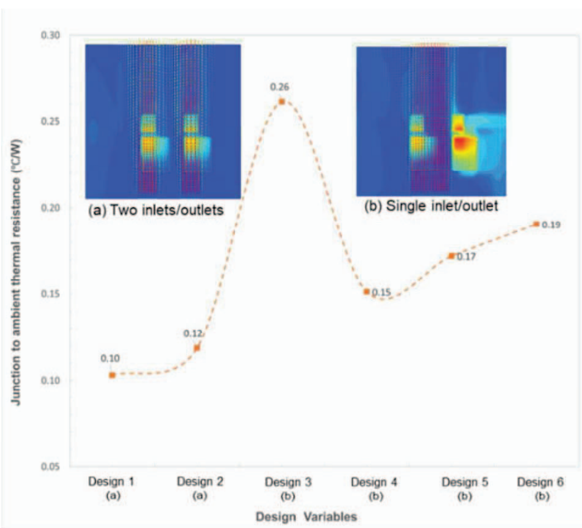


Fig. 5. Simulated junction to ambient thermal resistance vs. different design parameters for (a) two inlets/outlets design and (b) single inlet and outlet design for the suggested power module

The change of simulated junction to ambient thermal resistance with different design parameters for the proposed power module is given in Fig. 5. Overall, two designs for the inlet/outlet configurations are considered in this study. One is the design configuration with single inlet and single outlet (i.e. Configuration-b) and the other is the configuration with two inlets and outlets (i.e. Configuration-a). Fig. 5 shows that the power module with Configuration-a (i.e. configuration with two inlets and two outlets) has lower junction to ambient thermal resistance than the power module with Configuration-b, suggesting the power module with Configuration-a has better thermal performance than the power module with configuration-b. Take a further study to Fig. 5, the design 1 from Configuration-a produces the lowest thermal resistance among the all the designs in both of Configuration-a and Configuration-b, indicating the power module with design 1 produces the best thermal performance.

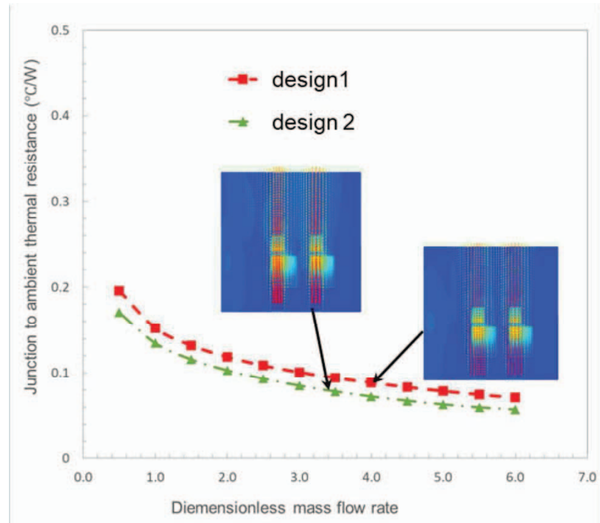


Fig. 6. Simulated junction to ambient thermal resistance vs. different mass flowrate for power module with design Configuration a

Fig. 6 gives the change of simulated junction to ambient thermal resistance with different mass flowrate for power module with design Configuration a. It can be revealed from Fig. 6 that higher mass flowrate produces better heat dissipation performance. The flowrate has large effect on the heat dissipation performance when the dimensionless flowrate varies from 0.5 to 2.0. While the flowrate has less effect on heat dissipation performance when the dimensionless flowrate varies from 2 to 6. Dimensionless flowrate of 2~3 is set as the design point in this study.

TABLE I. TABLE I COMPARISION BETWEEN DSC POWER MODULE AND IMMERSION TWO PHASE COOLING POWER MODULE

Power Modules	Proposed Size	Heat dissipation capability (simulation results)
1. Double Side Cooling Power Module (Cold Plate / Cold Plate)	50mm (L) x 50mm (W) x **20mm (H)**	**600 W**
2. Immersion Two-phase Cooling Power Module (Liquid /Vapor Out; Dielectric liquid/vapor; SiC; SiC; Liquid In)	50mm (L) x 50mm (W) x **8mm (H)**	**1250W**

Further simulations have been performed to compare the cooling efficiency between the power module cooling at both sides and the power module with immersion two phase cooling. the simulation results are elaborated in Table I, which provides the comparison of form factor and heat dissipation capability between the DSC power module and immersion two phase cooling power module. In the simulation, we assume the footprints are same (50mm x 50mm) for these two types of power module. The required height for the DSC power module is 20mm but the required height for the immersion two phase cooling power module is 8mm only. With same operation conditions and allowable SiC junction temperature, the simulated heat dissipation capability for the DSC power module is 600W, while the simulated heat dissipation capability for the immersion two phase cooling power module is 1250W, which is more than 2 times of the heat dissipation capability of the DSC power module, indicating the high efficiency of the immersion two phase cooling power module.

IV. TEST VEHICLE ASSEMBLY

After the parametric optimization and design finalization, the proposed power module has been fabricated.

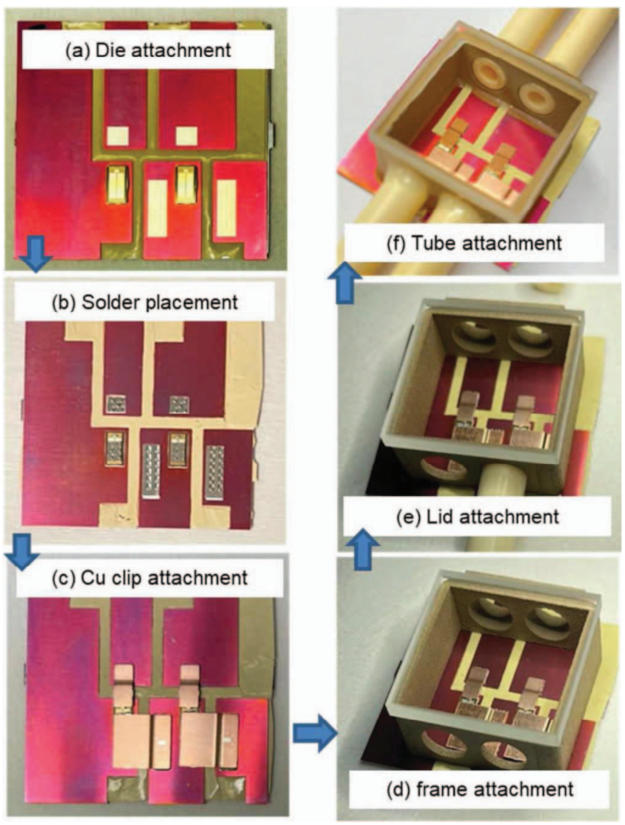


Fig. 7. Assembly process of the proposed immersion two phase power module.

The process flow for the power module assemble is illustrated in Fig. 7. The major assembly steps include: (a) the SiC power devices are attached to the customized copper lead frame by applying silver sintering die attach material [12,13]; (b) and (c) The copper clips are attached to the gate and source pads by using the preform solder material; (d) the cooling enclosure is fabricated with Polyphenylene sulfide (PPS) material and it is integrated with the power module with special sealant; (e) top glass lid is attached to the cooling enclosure and (f) the connector and Teflon tube are attached to the integrated power module for cooling media (dielectric coolant) circulation. The integrated test vehicle for the proposed immersion two phase cooling SiC power packages is presented in Fig. 8, which provides the photos of the fabricated power module test sample for (a) top view (from glass lid side) and (b) bottom view (from lead frame side).

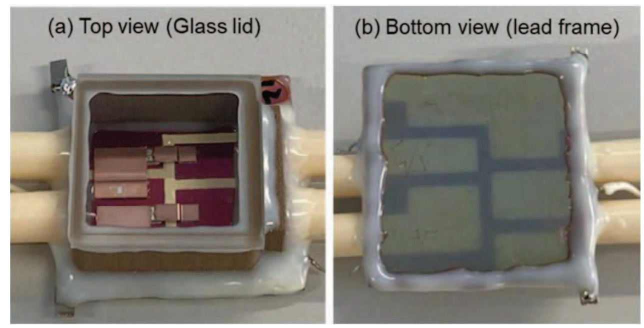
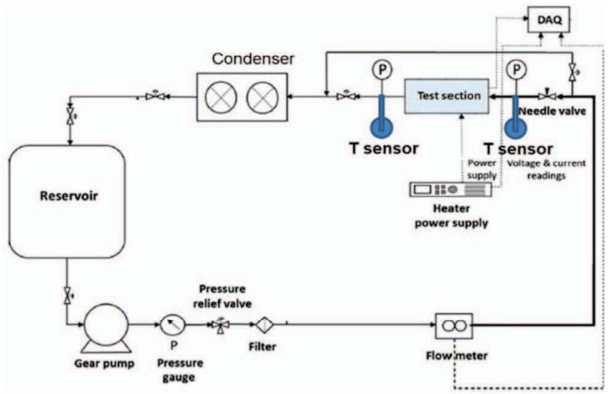


Fig. 8. Photos of the fabricated test sample: (a) top view (from glass lid side) and (b) bottom view (from lead frame side)

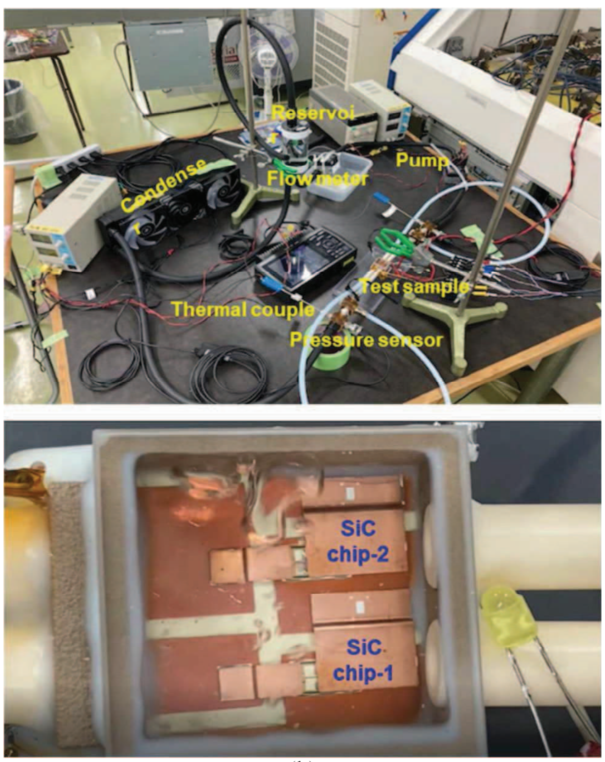
V. THERMAL PERFORMANCE CHARACTERIZATION

A test loop is set up to characterize the developed immersion two-phase power module and to evaluate its thermal performance. The system is shown in Fig. 9 for (a) schematics of the thermal test system and (b) photos of the test loop and test vehicle with dielectric coolant for thermal characterization. The system is majorly composed of a reservoir for the coolant storage, a gear pump to drive the flow, a condenser for vapor condensation, power sources to power on/off the SiC chips, flow meter for flowrate measurement, temperature and pressure sensors for temperature and pressure monitoring, valves to control the flow and a data logger for data acquisition. Novec HFE-7500 from 3M company is used as the coolant. The test is carried out by fixing the electrical current supplied to the SiC chips in the power module and fixing the inlet temperature of the coolant, but varying the coolant flowrate.

The SiC chip junction temperature is measured by utilizing the characteristics of the body diodes in the SiC chip. In general, the correlation between the junction temperature and the forward voltage of the body diode is nearly linear. Thus a change in junction temperature produces a corresponding change in junction forward voltage with a constant correlation factor, known as K factor. During the measurement, the K factor which represents the correlation between the temperature and forward voltage of the body diode is firstly calibrated. Then the forward voltage of the body diode is measured when the SiC chips are powered on and the junction temperature of the SiC chips is analyzed through the measured forward voltage and the calibrated K factor. The measured SiC junction temperature for the proposed power module is shown in Fig. 10, which gives the change of the SiC chip junction temperature with the lapse of time. For comparison, the simulated SiC chip junction temperature is added to this figure as well. We can observe from Fig. 10 that the uniformity of the junction temperature for chip #1 and chip #2 is within a reasonable range (<3%). Meanwhile, the simulated junction temperature coincides well with the measured junction temperature. Furthermore, by taking a close look at Fig. 10, it can be found that the junction temperature of the SiC chip increases very quick and reaches to the near-stable temperature within 2 seconds after the chips are powered on, indicating the importance of effective cooling for the power module to avoid the temperature overshooting.



(a)



(b)

Fig. 9. Test loop of thermal characterization for the devloped power module (a) diagrame of the test setup and (b) pictures of the test loop and test sample with dielectric coolant

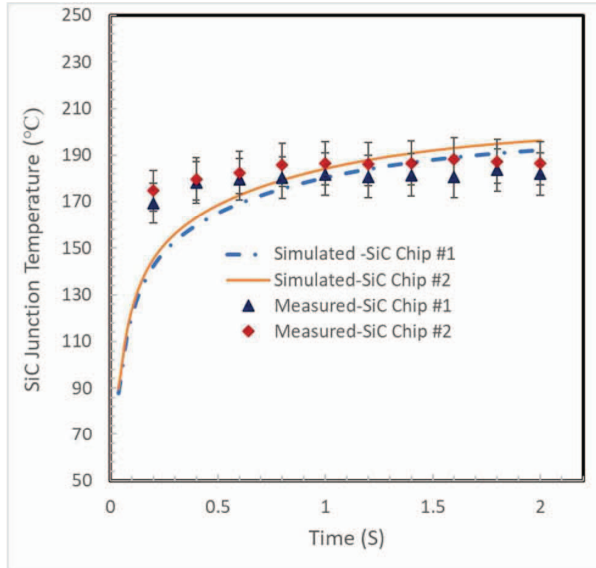


Fig. 10. Measured and simulated junction temperature vs. the lapse of time

VI. Summary

In this study, a SiC power devices equipped power module with immersion two phase cooling solution is proposed for automotive applications. The CFD modeling and heat transfer simulations have been carried out to assess the heat dissipation capability of the power modules with different design parameters. Meanwhile, the comparison of the thermal performance between the developed immersion two phase cooling power module and the existing DSC power module is performed. Lastly, the proposed power module is fabricated, and the thermal characterization is conducted. The SiC chip junction temperature is measured. In summary, the below findings are drawn in this study:

- The power module developed and demonstrated in this study is with light weight and thin structure
- Multi-inlet design (Configuration a in this study) is one of the most effective designs with high cooling efficiency for the proposed immersion two-phase cooling power module.
- Comparing to the lead frame based power module with DSC solution, the power module with immersion two phase cooling solution is with 60% of size reduction and 100% of heat dissipation capability improvement for the same power delivery requirement and operation conditions. This enhancement is attributed by the direct device level cooling of the immersion two phase power module.

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