Innovative Heat Removal Structure for Power Devices - the Drift Region Integrated Microchannel Cooler

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Innovative heat removal structure for power devices - the drift region integrated microchannel cooler

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Abstract— **Liquid microchannel cooling is approved to be a compact and high-performance solution to deal with the thermal requirements of power devices and modules. This is due to the large heat exchange surface, the high heat transfer coefficient and the minimized thermal interfaces that microchannel coolers offer. This paper reports an original concept for efficient thermal management of power devices based on the integration of a microchannel cooler, including numerous parallel through wafer fluid vias, directly into the drift region of the power device. Simulation results proved that no negative side effects are resulting from this integration regarding the electrical performance of the device. The effectiveness of the proposed cooling technique was evaluated with hydraulic and thermal numerical models. Vertical power diodes with integrated microchannel cooler were fabricated and characterized to demonstrate the feasibility and the effectiveness of the concept.**

I. INTRODUCTION

Numerous research studies have been realized in order to develop and to evaluate the interest of liquid microchannel cooling for planar integrated circuits [1, 2] and for 3D chip stacks configurations [3, 4]. Although it has been demonstrated that reducing the hydraulic diameter of channels allows to greatly increase the heat transfer coefficient and the ratio surface/volume of the heat exchanger, the resulting significant increase of the pressure drop values must also be taken into consideration. In addition, in standard power modules, the cooling fluid is flowing in lateral microchannels in the parallel plan of the module [5] which causes temperature gradients along the cooled area [6] due to the warming up of the fluid.

This paper presents an innovative concept for liquid microchannel cooling of power devices and modules providing a high performance heat removal and a uniform temperature distribution whereas drastically reducing the pressure drop values. This new concept, called the Dift Region Integrated Microchannel cooler (DRIM cooler), is based on the integration of multiple microchannel fluid vias directly into the drift region of the power device. Vertical power diodes integrating the DRIM cooler were fabricated and experimentally tested. Electrical tests were carried out to measure their direct and reverse biased characteristics. At the end of the paper we present the experimental setup allowing the measurement of the thermal and hydraulic performances of the devices with DRIM cooler.

II. DESIGN AND REALIZATION

A. Concept

The concept of the DRIM cooler is to etch directly into the active region of the power device numerous parallel microchannels which will serve as fluid vias enabling the circulation of a dielectric cooling fluid. Fig. 1 shows a schematic view of the principle using a vertical power diode as example.

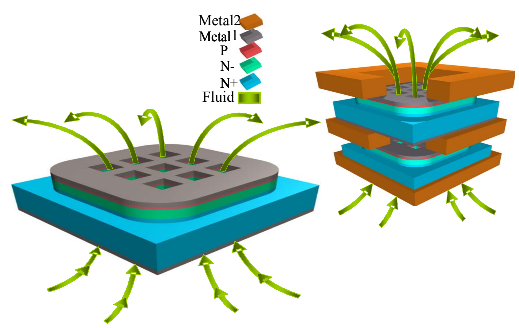

Figure 1. Schematic view of the cooling concept with the microchannel cooler integrated in the drift region of a vertical power PIN diode and application of the cooling concept for 3D chip stack configuration.

As it can be seen in fig.1 the voltage handling capability of the device is assured by a peripheral deep trench termination [7]. The multiple parallel microchannels (MC) with small length, take advantage of this edge termination technique to offer an effective management of the electric field at the interface between the drift region of the power device and the dielectric cooling fluid. MC length is equal to the thickness of the substrate, providing very low pressure drop values. Besides, the numerous MC with small hydraulic diameter

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(50µm - 400µm) offer a high heat transfer coefficient (more than 10000W/m^2/K) and a greatly expanded exchange surface (e.g. for a device of 1cm2 with 500µm thickness of the substrate where 10% of the total surface is occupied by square microchannels of 100x100µm^2 the exchange surface is equal to 2cm^2). Another important profit of this cooling concept is the resulting homogeneous temperature of the semiconductor chip due to the homogenous spread of parallel MC and the high thermal conductivity of silicon.

A key benefit of the concept is the possibility to distinguish thermal and electrical "exchange" surfaces, thus enabling advanced design packaging for power modules. Fig. 1 shows that the wire bonds can be replaced by massive copper connections surrounding the MC region. It allows the series implementation of multiple power devices in a 3D Power Chip on Chip configuration [8]. In this particular case the electrical contact can be realized only at the periphery of the device where a special area is reserved not occupied by the channels and where the electrical connection can be realized. The homogenous repartition of the current must then be assured by a thick metal layer at the electrodes of the devices.

B. Theoretical results

A detailed analysis with 2D finite element simulations (Silvaco) was realized in order to examine the possible effects considering the electrical performances of a vertical power diode with DRIM cooler. The obtained results were compared with the optimum case of the infinite plane junction for a device having the same physical parameters. In fig. 2 is depicted the electric field distribution contours and the equipotential lines at a reverse voltage of 800V for a vertical PIN diode with 50x50µm^2 fluid via passing through the drift region of the diode and filled with a dielectric material.

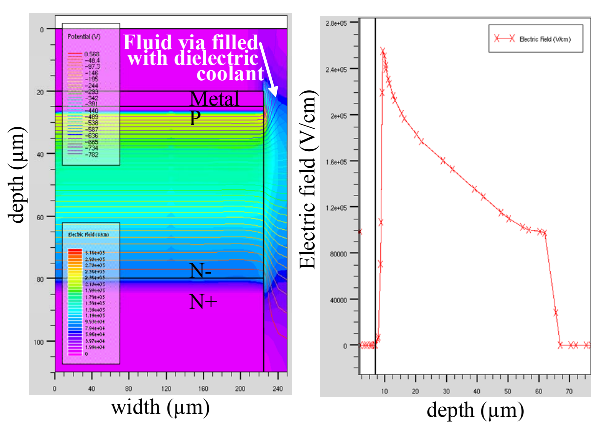

Figure 2. Electric field distribution contours and equipotential lines for 800V reverse biased PIN diode with 50x50µm^2 width microchannel fluid via filled with a dielectric material and passing through the drift region of the device; Electric field cross sectional view at the interface Si/dielectric fluid. The simulated structure has the following characteristics – 90µm thickness of the Si substrate where 25-28µm is the depth of the P region with 3×10^{17}/cm3 concentration, 28-80µm is the drift N region with 2×10^{14}/cm3 concentration and 80-110µm is the N+ region with 1×10^{19}/cm3 concentration.

The results show that the integration of the microchannel fluid vias into the drift region does not affect the voltage handling capability of the device. Fig. 2 shows a conformal and close to ideal electric field distribution. Nevertheless, voltage and current ratings are not affected by the integration of the MC. Especially, the reduction of the active area cross section is greatly compensated by the enhanced heat removal.

Fig. 3 shows one of the key benefits of the proposed cooling technique (square vertical microchannels) compared with another cooling approach (square lateral microchannels) which relies on the circulation of the cooling fluid in the parallel plan of the module or the PN junction through the realized on the backside of the semi-conductor device or the module microchannels.

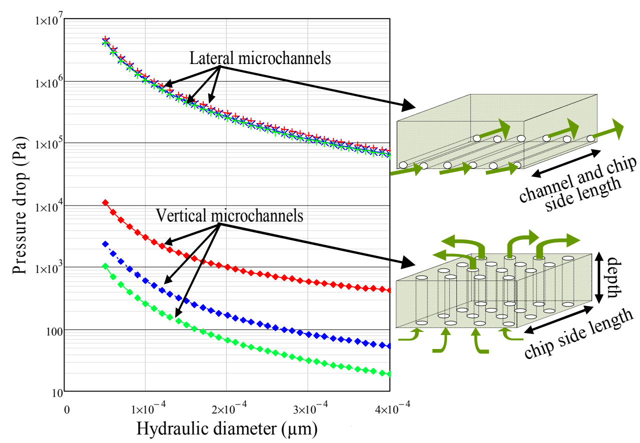

Figure 3. Pressure drop values in function of the hydraulic diameter for different chip side lengths - 5mm red curve, 10mm blue curve, 15mm green curve

The pressure drop values represented in fig. 3 were calculated as function of the hydraulic diameter of the channels for a constant fluid flow rate (0.12L/min determined so that the temperature difference of the cooling fluid, water in this case, from the inlet to the outlet of the channels is 50ºC and the power losses are 400W) and fixed exchange surface (10% of the total surface of the chip is occupied by MC) when varying the chip side length (5mm, 10mm, 15mm for 500µm thickness). With these parameters the flow regime is determined to be laminar. In the case of vertical MC the variation of the chip side length causes a variation of the number of channels in parallel but their length remains constant and equal to the chip thickness (500µm in our case) and thus the pressure drop values decrease. In the case of lateral MC the variation of the chip side length causes a variation of the number of channels in parallel but also determines the length of the channels. Thus the pressure drop values remain identical. As it can be seen in fig. 3 for all hydraulic diameters the pressure drop values in the case of vertical MC are significantly lower compared with those for lateral microchannels.

Fig. 4 shows the numerical evaluation of the thermal performances of the DRIM cooler. The simulation represents the temperature distribution throughout the wall of a square MC of 50µm hydraulic diameter with 500µm length with dielectric coolant flowing through it with total flow rate of 0.27L/min (the temperature difference of the cooling fluid from the inlet to the outlet of the channel is 50ºC and the total power heat is 400W). The heat transfer coefficient is in that case $1.2*10^4$W/m^2/K and the thermal resistance 0.08K/W.

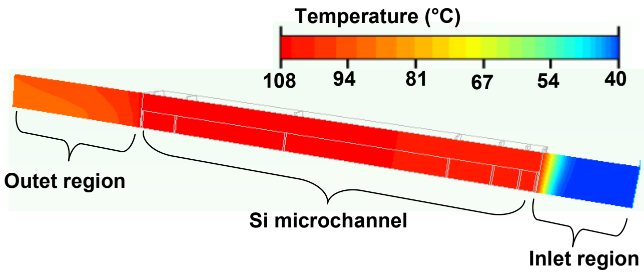

Figure 4. Temperature distribution at the wall of a silicon MC with inlet and outlet region of the dielectric coolant.

As it can be seen on fig. 4 the temperature throughout the silicon microchannel is rather homogenous.

C. *Realization*

In order to evaluate the performance of this new cooling concept vertical power diodes with DRIM cooler were fabricated. In our case 500µm N+ type (100) substrate plus 55µm lightly doped (20 Ω cm) epitaxial layer was used for the realization of the prototypes. After the deposition of the 3µm thick aluminum layer on the both sides of the silicon substrate a double side lithography step was realized to distinguish the different patterns. Top and bottom patterns are different because of the surface peripheral deep trench termination needed to ensure the voltage handling capability of the devices. The through wafer fluid vias were realized by Deep Reactive Ion Etching (DRIE) performed on both sides of the silicon substrate. We used the aluminum metal layer as masking material. No post processes for surface or wall treatment were performed after the silicon etching step. Fig. 5 shows pictures of the realized prototypes.

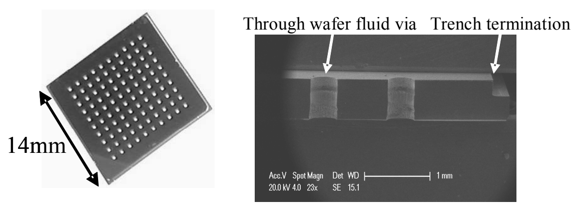

Figure 5. Photograph and cross sectional SEM image of the realized power diode with DRIM (200µm diameter of the fluid vias) cooler.

III. PRACTICAL RESULTS AND DISCUSSION.

A. *Electrical characterization of the device with DRIM cooler*

For the experimental validation of the electrical performances, the fabricated power diodes with DRIM cooler were packaged and passivated with silicone oil. Fig. 6 shows the realized package.

The periphery of the cathode not occupied by the microchannels was soldered on a pcb track especially designed in order to optimize the power interconnections and to allow the use of Kelvin probe measurement technique. The anode was wire bonded with multiple bond connections spread all over the surface periphery of the device in order to improve the homogenous distribution of the current.

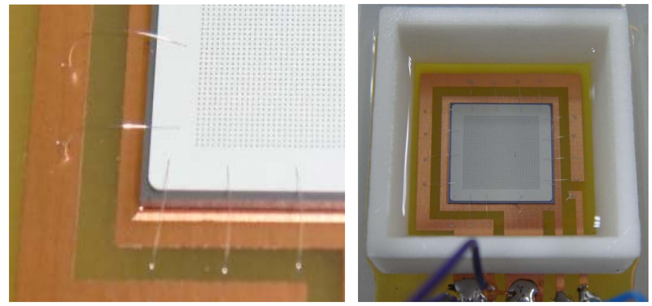

Figure 6. Photograph of the realized package.

The packaged prototypes were experimentally tested with a static characteristic power curve tracer HP 371A. Fig. 7 shows the reverse biased static characteristic of the diode with DRIM cooler (prototype fig. 6). The device achieved a breakdown voltage of 300V with a leakage current of 1µA.

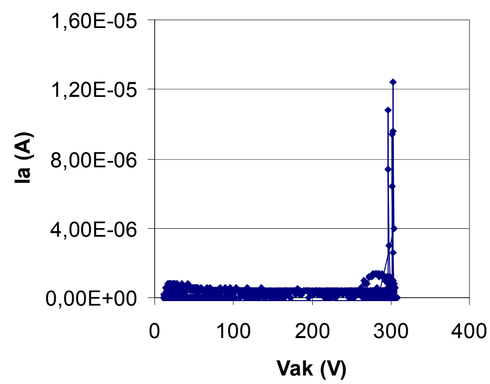

Figure 7. Reverse biased characteristic of the diode with DRIM cooler.

This result is only partial because the device was initially designed for a breakdown voltage of 600V and it is supposed to handle such voltage breakdown levels. In our case the passivation of the device and the trench terminations was realized in a non protected atmosphere which may justify this result. Additional experimental measurements should be carried out in order to identify the reason of the premature breakdown of the device. Fig. 8 represents the forward biased characteristics of the same diode. Although the Kelvin probe measurement this result is below our expectations. Indeed the forward voltage drop was expected to be 1.5V at I_{AK}=20A instead of 3V obtained in practice. This large difference can not be associated to the reduction of active surface since it only represents 10% of the active surface. Again additional work will have to be carried out to investigate this issue. Nevertheless both static results are greatly encouraging and allow to continue the thermal and fluidic characterizations.

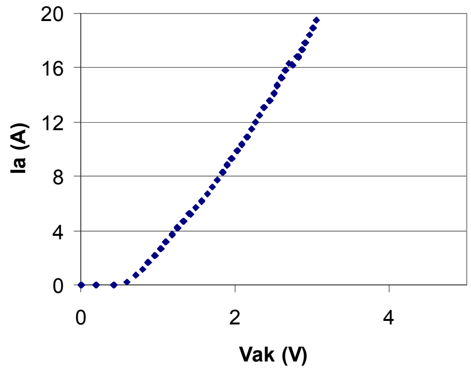

Figure 8. Forward biased characteristic of the diode with DRIM cooler.

B. Thermal characterization of the device with DRIM cooler

Fig. 9 shows a picture of the experimental setup designed for the hydraulic and thermal characterization of the DRIM cooler concept which is based on the measurement of the junction temperature of the device with thermosensitive electrical parameters and the measurement of the pressure drop values needed for the identification of the pumping power necessary to cool the device. A vacuum pump is used for evacuating the air from the hydraulic circuit before its filling and for degassing the fluid. The goal of this procedure is to reduce the vapor or the air bubbles in the circuit and especially in the DRIM cooler. The diode with DRIM cooler (device under test) is fixed between two electrodes in aluminum. The electrical contact between the periphery of the device and the electrodes is made by applying a pressure force. In both electrodes, a circular duct is machined for the fluid circulation. Two holes allow the measurement of the pressure drops by a differential pressure sensor. The flow rate is measured with an ultrasonic flowmeter.

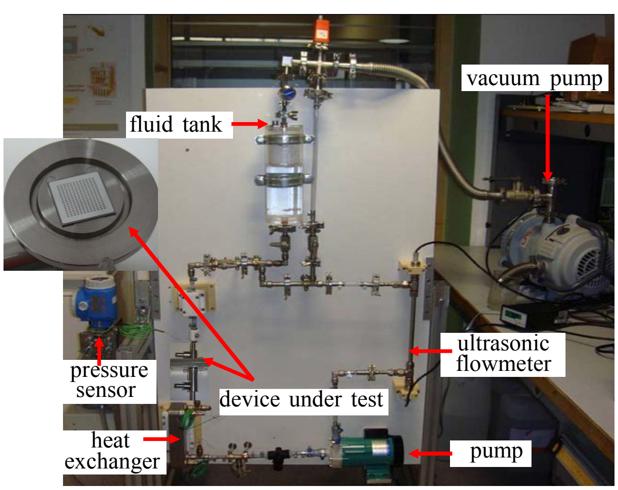

Figure 9. Experimental setup for the validation of the DRIM cooler concept.

The first step of the DRIM cooler characterization is the measurement of the pressure drops. Because no current circulates in the device, water was used in order to compare first experimental and simulation results. Fig. 10 shows a good conformity of theoretical and practical results.

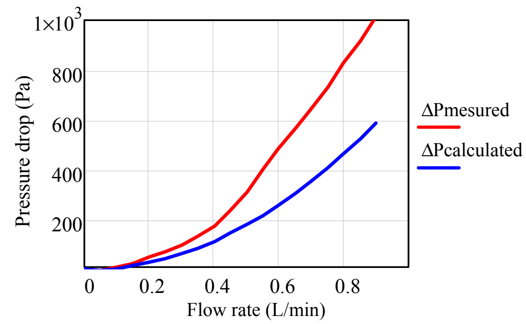

Figure 10. Measured and calculated pressure drop values versus flow rate for a diode with DRIM (400x400µm^2 MC with 15% occupation) cooler.

IV. Conclusion

An original concept for efficient direct cooling of power electronic devices was presented. It is based on the integration of numerous microchannel fluid vias directly into the drift region of the power device. The small hydraulic diameter of the fluid vias offers a high heat transfer coefficient and thus excellent thermal performances are expected. The exchange surface is greatly developed with the multiple parallel channels with small length which are also providing low pressure drop values. The practical characterization of the fabricated prototypes proves that the integration of microchannels in the drift region of the device is feasible but must be improved.

Acknowledgment

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