Abstract—A diamond heat spreader has been applied on the hybrid Si microcooler for the improvement of the hotspots cooling capability for GaN devices. To dissipate the high concentrated heat flux, the effective heat spreading capability of the diamond heat spreader, with a copper heat spreader, and without a heat spreader have been made among the structures with a diamond heat spreader. The improvement of hotspot cooling capability using a diamond heat spreader is more pronounced for the thin chip of thickness 100 μm. Two types of diamond of different thermal conductivities are tested and compared.

Index Terms—Diamond heat spreader, GaN device, hotspot thermal management, microjet array impingement.

I. INTRODUCTION

HIGH heat flux removal is a major consideration in the design of a number of microelectronic devices, such as power amplifiers [1], [2]. The operation of a GaN high electron mobility transistor on a silicon chip posts huge challenge to the thermal management, as the heat dissipation concentrates on tiny areas, which could lead to highly nonuniform temperature distribution, thus diminishing the device performance and adversely impacting reliability. The effective thermal management will be a key to enable the technology to reach its full potential [3]–[5]. Both microchannel and microjet heat sinks can dissipate the high heat fluxes anticipated in high power electronic devices [6]–[8]. Liquid jet impingement can provide a high heat transfer coefficient, when arranged in arrays. Brunswiler et al. [9] created a series of microjet arrays with branched hierarchical parallel fluid delivery and return architectures. The peak heat transfer coefficient measured was $8.7 \times 10^4$ W/m²K. Compared with the impinging microjet, the microchannel has a lower averaged heat transfer coefficient. However, the coolant can exchange energy with a larger effective surface area with multiple walls within each channel. Colgan et al. [10] presented a Si microchannel cooler and optimized the cooler fin for cooling a very high power chip, and 300-W/cm² uniform heat flux was dissipated. The hybrid microcooler, combining the merits of both the microjet array impingement and the microchannel flow, has been applied for cooling a high-power device [11], [12]. To dissipate the high concentrated heat flux, the effective heat spreading capability is quite significant as well. A chemical vapor deposition (CVD) diamond heat spreader of high thermal conductivity turns out to be a great candidate for this application [13]–[17]. Rogacs and Rhee [18] conducted the numerical simulation to evaluate the thermal effect of the diamond heat spreader for a small heat source. Calame et al. [19] conducted the experimental and simulation analyses on the microchannel cooler capped with a layer of diamond, and better cooling performances were exhibited than SiC alone. According to Liu’s numerical calculations, a thin diamond heat spreader could enable ~10% to 20% decrease in the whole thermal resistance of the heat sink [20].

In this paper, the enhancement of heat dissipation capability using a diamond heat spreader on a Si hybrid microcooler has been investigated through experiments and simulations. The designed cooling system is illustrated in Fig. 1. A customized thermal test chip of eight tiny hotspots is fabricated, and bonded with a Si cooler and a diamond heat spreader through the thermal compression bonding (TCB) process. The Si hybrid microcooler, combining the microjet impingement array and the microchannel flow, can achieve a high heat transfer coefficient with a low pumping power requirement. The jet flow from the microjet plate impinges on the top wall, and is constrained to flow along the microchannel to the outlet trench. A diamond heat spreader is directly attached between the chip and the cooler. Cooling performance comparisons have been made among the structures with a diamond heat spreader, with a copper heat spreader, and without a heat spreader. The improvement of hotspot cooling capability using a diamond heat spreader is more pronounced for the thin chip of thickness 100 μm. Two types of diamond
The thermal effects of the heat spreader thickness and the bonding layer are studied. For a GaN device, the dissipated power densities with various cooling solutions are evaluated, while maintaining the peak gate temperature under 200 °C. The consistent results of experiments and simulations have demonstrated high cooling capability improvement using the diamond heat spreader on the microfluid cooler.

### II. Fabrication and Experiments

The experimental tests have been implemented on the customized Si thermal test chip of size 7 × 7 mm², with eight hotspots evenly located in line, as illustrated in Fig. 1. The size of each hotspot is 450 × 300 μm², which is a good approximation of one GaN unit area composed of ten gate fingers of 300-μm gate width, 0.3-μm gate length, and 45-μm gate pitch. The space between each hotspot is set to be the same as that of the transistor banks of the GaN device, which is 690 μm. The highly doped n-type resistors are built on the Si test chip as hotspot heaters. The resistivity measurement of the finished wafers shows good consistency [21].

The diamond heat spreaders supplied by Element Six are prepared through microwave CVD, and metalized with a thin Ti/Pt/Au layer (total thickness around 1 μm) for tight bonding with a Si chip and a microcooler. The size of the heat spreader is 9 × 9 mm², and its thickness is 400 μm. Several types of diamond heat spreader of different thermal conductivities are considered in this paper, as listed in Table I.

<table>
<thead>
<tr>
<th>Diamond type</th>
<th>Thermal conductivity at 25°C</th>
<th>Thermal conductivity at 150°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>2000 W/mK</td>
<td>1500 W/mK</td>
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<tr>
<td>Type 2</td>
<td>1500 W/mK</td>
<td>1400 W/mK</td>
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<tr>
<td>Type 3</td>
<td>1800 W/mK</td>
<td>1500 W/mK</td>
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<tr>
<td>Type 4</td>
<td>1000 W/mK</td>
<td>900 W/mK</td>
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The hybrid microcooler is fabricated by bonding two Si plates together, one is with 18 microchannels and the other is with a 14 × 18 microjet array. The internal dimensions of the microcooler have been optimized, considering the combined effect of heat convection and conduction. The nozzle diameter is 100 μm, depth is 400 μm, and pitch is 350 μm. The channel width, fin width, and depth are 250, 100, and 250 μm, respectively. The channel length is 5 mm. The size of the outlet trench is 6.5 × 0.5 mm², and the distance between the nozzle array and the trench is 4.5 mm. The microchannels or microjets are etched on different wafers with the deep reactive ion etching process. After etching, the wafer is metalized with 4-μm Au/Sn solder by evaporation. Then, these wafers are diced into a single plate, and chip-level bonding is conducted to bond the microchannel plate and the microjet plate together, as shown in Fig. 2. Plate bonding is carried out through the TCB process, in which the 280 °C chuck holding time is 2 min, and the compressive force is 49 N.

After the assembly of the microcooler, the outside surfaces of the bonded microcooler are then metalized for the following bonding process. All the prepared components, including the chip, the heat spreader, and the microcooler, are bonded in one step through the TCB process under the same condition as above. The soldering quality at the bonding interface was checked using both X-ray and scanning acoustic microscopy. No void was detected in the bonding layers. To prepare the test vehicle, the bottom side of the microcooler is attached on the Printed Circuit Board using epoxy, and the test chip on the top is wire bonded for electrical connection, as shown in Fig. 3. Copper of measured thermal conductivity 386 W/mK (uncertainty 3.5%) is normally used as the heat spreader material. Another test vehicle with a copper heat spreader of the same size was fabricated for performance comparison. To achieve reliable assembly, the reflow process with a 20-μm-thick Au/Sn preform solder is used for components bonding, in which the peak temperature is ~230 °C.

The dc power is supplied to the hotspot heaters on the thermal test chip. A water coolant is driven through the flow loop using a microgear pump. This pump forces the water through a 15-μm filter and a flow meter before entering the microcooler. The heated water from the microcooler is cooled down by a water bath, and then flows back to the cooling system. A differential pressure transmitter is attached to the manifold to measure the pressure drop. The inlet water ambient temperature is ~25 °C. The test chip temperature at steady
state is measured and recorded using an infrared (IR) camera. In the test, the steady state (temperature variation ±0.1 °C) is usually reached within 30 min. Prior to the measurement, the chip is coated with a thin layer of matt black paint, and the emissivity of the coating is estimated at 0.9. The temperature measurement uncertainty is around ±3.5%.

III. THERMAL/FLUID SIMULATION

The simulation models are constructed using COMSOL Multiphysics that runs the finite-element analysis together with adaptive meshing and error control. The built-in fluid flow and heat transfer interfaces are used in the 3-D model that couples both solid and fluid parts. Due to the symmetries in the system, a quarter of the structure with symmetrical boundary conditions is constructed, as illustrated in Fig. 4.

The solution was tested for mesh independence by refining the mesh size. The velocities and the temperatures matched within 0.1% for both the mesh sizes. The convergence criterion of the solutions is $10^{-6}$. The viscous heating feature is considered in the heat transfer interface. No slip boundary condition is applied for stationary walls. Natural convection from the topside of the test vehicle is also included. The temperature-dependent thermal conductivity of Si is considered, the expression of which is $k_{Si} = 152 \times (298/T)^{1.334}$. The thermal conductivity of a Au/Sn material is assumed to be constant, which is 57 W/mK. A Au/Sn bonding layer of 5-μm thickness is considered between the Si and diamond contact interfaces. The models without and with a heat spreader consist of >2.06 and 2.25 million tetrahedral elements, respectively. The element size of the fluid part is calibrated for fluid dynamics, while that of the solid part is calibrated for general physics. High heat fluxes are loaded only on the tiny areas of the hotspot heaters.

IV. RESULTS AND DISCUSSION

First, the experimental tests are performed on the thermal test chip of 200-μm thickness. The volume flow rate in the microcooler is set at 400 mL/min, and the pumping power is ~0.2 W. The heating power from 10 to 100 W has been loaded into eight hotspot heaters (each of size $450 \times 300 \mu m^2$). The steady-state simulation is performed with the loading and environment conditions set according to the tests. Based on the estimated low Reynolds number in the microcooler, it is considered to be operated in laminar regime. The experimental and simulation results are shown in Fig. 5. A Type 1 diamond heat spreader of thickness 400 μm is used in this test.

Without a heat spreader, the structure can dissipate 54-W heating power (hotspot heat flux of 5 kW/cm²), and the maximum hotspot temperature is 136 °C. With the copper heat spreader, the structure can dissipate 54 W, and the maximum hotspot temperature is 124 °C. By doubling the copper thickness, the improvement is <1%. The directly attached diamond heat spreader can enable highly improved heat dissipation capability for the cooling system. For 54-W power dissipation, the maximum hotspot temperature can be reduced by ~25.7% compared with the one without a spreader, and 17.1% compared with the one with the copper heat spreader. To maintain the chip temperature under 180 °C, the structure with the diamond heat spreader can dissipate ~100 W (9.2 kW/cm²), while that without a spreader can dissipate ~70 W, and the one with the copper heat spreader can only dissipate ~80 W.

As shown in Fig. 5, excellent agreement has been obtained between the experimental and simulation results, suggesting that the thermal performance is accurately simulated. In the hybrid microcooler, the spatially averaged heat transfer coefficient at the top impingement wall in the microchannel is ~11.3 × 10^4 W/m²K, and the local value in the stagnation zone is much larger. The temperature distribution on the top surface of the chip from the test is illustrated in Fig. 6.
The maximum temperature occurs at the hotspot located near the Si chip center, as shown in Fig. 6. For 54-W heating, the maximum temperature of the hotspot located near the chip edge is 8 °C lower than the center one in the structure without a heat spreader. The diamond heat spreader can maintain similar peak hotspot temperature, and enables 2 °C peak temperature differences between the hotspots located near the edge and the center. The peak hotspot temperature variation rate ($\alpha_T$) among all the hotspots is calculated to evaluate the cooling performance. This rate is represented as $\alpha_T = (T_E - T_C)/T_A$, where $T_C$ and $T_E$ are the peak temperatures of the hotspots located near the center and the edge, respectively, and $T_A$ is the average value of the peak temperatures of all the eight hotspots. In the current case, for 54-W power dissipation, the rate $\alpha_T$ of the structure without a heat spreader is $\sim6.2\%$, while that with the copper heat spreader is $\sim5.9\%$, and the one with the diamond heat spreader is as small as $2.5\%$.

Another diamond of different thermal conductivities has been used in the thermal test for comparison, as is shown in Fig. 7. Type 1 diamond was used in the above tests. The thermal conductivity of Type 2 diamond drops slightly from room temperature to higher temperature. The results show that similar cooling capability has been achieved using these two types of diamond. To dissipate the same heating power, the maximum hotspot temperature rise using Type 2 diamond instead of Type 1 diamond is $<2\%$, and the increase in the rate $\alpha_T$ is $<0.4\%$.

More experiments and simulations have been conducted on the thin test chip of 100-μm thickness, which means shorter heat conduction path from the heat source to the cooling solution. The comparison results are shown in Fig. 8. More pronounced improvement of the hotspot cooling capability has been achieved using the Type 1 diamond heat spreader in this case. Compared with the results shown in Fig. 5, only slight temperature decrease is enabled by merely reducing the chip thickness from 200 to 100 μm. For 70-W heating, the maximum temperature decreases by $<2\%$. However, with smaller thermal resistance between the heat source and the heat spreader, much better heat dissipation capability has been achieved. With the diamond heat spreader, 110-W heating power (10.2 kW/cm²) can be dissipated while maintaining the maximum hotspot temperature under 160 °C. To dissipate 70-W heating power, the maximum hotspot temperature can be reduced by 27.3% with the copper heat spreader, and 40.4% with the diamond heat spreader. The concentrated high heat flux from the tiny hotspot is effectively reduced for the bottom jet-based microcooler to handle. Fig. 9 illustrates the heat flux distribution on the top surface of the Si microcooler for the structure with and without
a diamond heat spreader. The enhancement effect is quite obvious.

Smaller and more uniform heat flux has been enabled using the diamond heat spreader. The maximum heat flux in Fig. 9(a) is $\sim 2.66 \text{ kW/cm}^2$, while that in Fig. 9(b) is only $\sim 0.39 \text{ kW/cm}^2$, suggesting that the concentrated heat flux has been reduced to 14.7% using the diamond heat spreader. The maximum thermal resistance of the whole cooling structure, which is related to the total heating power and the maximum temperature of the cooling structure, can be reduced by 72.5% with diamond for the hotspot thermal management.

V. THERMAL EFFECT INVESTIGATION

More simulations have been performed to investigate the effect of the diamond heat spreader thickness on the thermal performance of the structure with a 100-μm-thick test chip. The thickness of the heat spreader is changed from 100 to 700 μm. The variations in the maximum hotspot temperature and the maximum heat flux at the top surface of the Si microcooler are analyzed, as illustrated in Fig. 10.

A Type 1 diamond heat spreader is used in this simulation. By increasing the heat spreader thickness, reduced temperature and heat flux can be achieved. The heat spreader used in the tests is 400-μm thick, and the thermal performance can be slightly improved by increasing the thickness to 700 μm. The effect is more sensitive by increasing the thickness from 100 to 400 μm, where the maximum hotspot temperature and the heat flux can be reduced by $\sim 12.1\%$ and 62.3%, respectively. The temperature distribution is also affected. For 110-W power heating, the variation rates $\alpha_T$ of 6.9%, 3.2%, and 2.6% are achieved with the diamond heat spreader of thickness 100, 400, and 700 μm, respectively.

Four types of diamond heat spreader of different thermal conductivities, which are listed in Table I, are analyzed and compared, as shown in Fig. 11. The cooling capabilities of the structure with Types 1–3 are quite similar. The maximum hotspot temperature rise by changing the heat spreader from Type 1 to Type 4 is $\sim 8\%$. With the Type 4 heat spreader, for 110-W power dissipation, the peak temperature variation rates $\alpha_T$ is $\sim 4.9\%$, which is higher than Type 1 (3.2%) and Type 2 (3.8%). Even so, with the Type 4 diamond heat spreader of relatively low thermal conductivity, 110-W heating power can be dissipated, and the maximum hotspot temperature is $\sim 175$ °C.

There are two bonding layers in the structure with the diamond heat spreader, which are quite critical to assure reliable components assembly and low thermal resistance. In the experimental tests, the thickness of both the layers is $\sim 5$ μm. Fig. 12 shows the temperature profile vertically from the Si chip to the microcooler. To dissipate 110-W power, the temperature rise caused at the chip–diamond bonding layer is $\sim 8.1$ °C, while that at the diamond–cooler bonding layer is negligible. The bonding layer on the topside of the heat spreader, which is more close to the heat source, has stronger effect on the hotspot cooling. Further simulation has shown that the thermal performance is quite sensitive to the thickness of the bonding layer at chip–diamond interface. By increasing the thickness from 5 to 10 μm, the temperature rise will increase by 8.8%, and if from 5 to 20 μm, the temperature rise will increase by 12.9%. No obvious temperature increase is observed by doubling or quadrupling the current thickness of the bonding layer at the diamond–cooler interface.

VI. HEAT DISSIPATION CAPABILITY OF GaN DEVICE

In the above experiments and simulation, one hotspot heater is used to mimic the heating area of one GaN unit consisting
of ten gate fingers, and consistent results have been obtained. In this paper, using the same simulation scheme for steady-state study, a model considering the heat producing regions of gate fingers has been built to evaluate the thermal performance of the GaN transistor with the designed cooling solution.

A number of assumptions were made to limit the scope of the investigation. Based on the one-quarter model shown in Fig. 4, the cooling structure under one hotspot is considered in the model illustrated in Fig. 13. Instead of one hotspot, in this case, the heating regions of ten gate fingers (each of size $300 \times 0.3 \, \mu m^2$) are constructed. This model considers a 2-\(\mu m\)-thick GaN layer of the thermal conductivity $k_{GaN} = 141 \times (298/T)^{1.211}$ on the top of the Si substrate. The thermal boundary resistance is included between the GaN layer and the Si substrate, and the value is assumed to be $3.3 \times 10^{-8} \, m^2K/W$ [22]. The models without and with a heat spreader consist of $>1.96$ and $2.07$ million tetrahedral elements to be mesh-independent. The load and condition settings for the fluid inside the microcooler are the same as the model shown in Fig. 4.

The results displayed in Fig. 14 show that, with the Type 1 diamond heat spreader and 0.2-W pumping power for the microcooler, to maintain the peak gate temperature under 200 °C, the heat power density of 4.02 W/mm (total heating power of 96.5 W) can be dissipated, which is $\sim 45.6\%$ more than that without a heat spreader, and around 28.4% more than the one with the copper heat spreader. As shown in Table II, both Type 1 and Type 4 can enable much better cooling capability for the concentrated high heat flux of the GaN device. For the chip of 200-\(\mu m\) thickness, compared with the structure without a spreader, the dissipated power density can be increased by 22% and 18% using Type 1 and Type 4 diamonds, respectively. For a thinner chip, the enhancement of the heat dissipation will be more pronounced.

### VII. Conclusion

The improvement of heat dissipation capability using the diamond heat spreader on the Si hybrid microcooler has been investigated for GaN devices. The experimental tests have been conducted on the customized thermal test chip of eight tiny hotspots to mimic eight GaN units. A test vehicle with a copper heat spreader was tested for comparison. Two types of diamond heat spreader of different thermal conductivities have been used in the test vehicles. High improvement of hotspot cooling capability has been demonstrated using the diamond heat spreader, especially for the case with a thinner thermal test chip. Using the Type 1 diamond heat spreader, 110-W heating power can be dissipated while maintaining the maximum hotspot temperature under 160 °C. To keep the maximum temperature under 160 °C, the structure without a heat spreader can only dissipate 65 W, and the one with the copper heat spreader can dissipate 80 W. The thermal effects of the heat spreader thickness, the diamond thermal conductivity, and the bonding layer have been analyzed and compared. In the test vehicle, the bonding layer of thickness around 5 \(\mu m\) has achieved high bonding quality and low thermal resistance. The bonding layer at the chip–diamond interface is quite critical to the thermal performance. The heat dissipation capability of the GaN transistors has been evaluated by constructing a gate finger model. Higher power density can be dissipated using the diamond heat spreader while maintaining the peak gate temperature under 200 °C. By effectively spreading the concentrated heat flux, the diamond heat spreader is verified to highly improve the hotspot cooling capability of the Si hybrid microcooler for GaN devices.

### REFERENCES


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