Optimizing Diamond Heat Spreaders for Thermal Management of Hotspots for GaN Devices

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Abstract

As devices become smaller while still requiring high reliability in the presence of extreme power densities, new thermal management solutions are needed. Nowhere is this more evident than with the use of Gallium Nitride (GaN) transistors, where engineers struggle with the thermal barriers limiting the ability to achieve the intrinsic performance potential of GaN semiconductor devices.

Emerging as a common solution to this GaN thermal management challenge are metallized diamond heat spreaders. In this paper, a diamond heat spreader has been applied with a hybrid Si micro-cooler for to cool GaN devices. Several different grades and thicknesses of microwave CVD diamond heat spreaders, as well as various bonding layers, are characterized for their thermal effects. The heat spreader is bonded through a TCB (thermal compression bonding) process to a Si thermal test chip designed to mimic the hotspots of 8 GaN units. The heat dissipation capabilities were compared through experimental tests and fluid-solid coupling simulations, both showing consistent results. In one configuration, using a diamond heat spreader 400µm thick with a thermal conductivity > 2000W/mK, to dissipate 70W heating power, the maximum chip temperature can be reduced by 40.4%, for test chips 100µm thick. And 10kW/cm2 hotspot heat flux can be dissipated while maintaining the maximum hotspot temperature under 160ºC. The concentrated heat flux has been effectively reduced by the diamond heat spreader, and much better cooling capability of the Si micro-cooler has been achieved for high power GaN devices.

Key words

CVD Diamond, GaN heat spreader, high power devices, thermal management

1. Introduction

GaN-based transistors and their related RF Power Amplifiers (PAs) have emerged as the leading solid-state technology to replace traveling wave tubes in radar, EW (Electronic warfare) systems, and satellite communications, and to replace GaAs transistors in cellular base stations. However, significant thermal limitations prevent GaN PAs from reaching their intrinsic performance capability. Metallized synthetic diamond heat spreaders have recently been used to address this thermal management challenge, particularly in cellular base station and military radar applications.

This article covers several important issues that advanced thermal solutions, particularly for RF power amplifiers, must address. Here, we are presenting new materials, such as CVD (chemical vapour deposition) diamond as a heat spreader to reduce overall package thermal resistance compared to today's more commonly used materials for thermal management. Also, mounting aspects and some new developments regarding the thermal resistance at the bonding interfaces to diamond heat spreaders are discussed.

2. CVD Diamond

Diamond possesses an extraordinary set of properties including the highest known thermal conductivity, stiffness and hardness, combined with high optical transmission across a wide wavelength range, low expansion coefficient, and low density. These characteristics can make diamond a material of choice for thermal management to significantly reduce thermal resistance. CVD diamond is now readily commercially available in different grades with thermal conductivities ranging from 1000 to 2000 W/mK. Also very important is the fact that CVD diamond has fully isotropic characteristics, enabling enhanced heat spreading in all directions. Figure 1 shows a comparison of the thermal conductivity of CVD diamond with other materials traditionally used for heat spreading purposes.

On-going development in the technologies to synthesize CVD diamond has enabled it to become readily available in volume at acceptable costs. Unmetallized CVD diamond heat spreaders are available today at a typical volume cost of $1/mm^3. Prices vary dependent on the thermal-conductivity grade used. In some instances, system operation at elevated temperatures can reduce both the initial cost of the cooling sub-system and the on-going operating cost as well. When applied with appropriate die-attach methods, diamond heat spreaders provide reliable solutions for semiconductor packages with significant thermal management challenges [1].

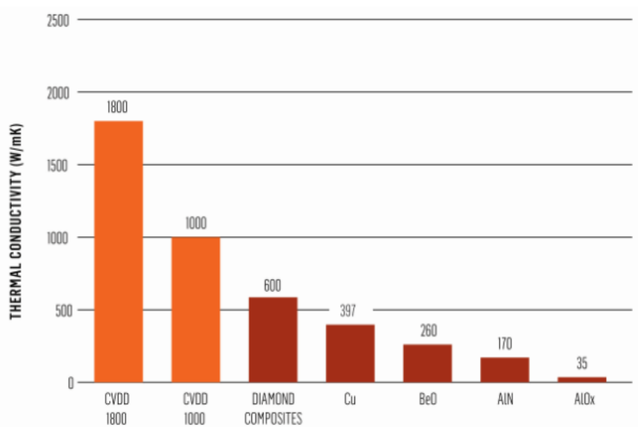

Figure 1: Comparison of thermal conductivity of CVD diamond and traditional heat spreading materials [1, 2]

3. Background information

High heat flux removal is a major consideration in the design of a number of microelectronic devices, such as power amplifiers [3, 4]. The operation of GaN high electron mobility transistor (HEMT) on silicon chip posts huge challenge to the thermal management, as the heat generation is concentrated in very small areas. This leads to significant thermal gradients and high operating temperatures which affect device performance. Also, it is considered general knowledge, that elevated temperatures are adversely impacting reliability. As a consequence, an effective thermal management is essential for the GaN device is important to reach its full potential [5-7]. As has been shown previously, both micro-channel and micro-jet heat sinks can dissipate high heat fluxes anticipated in high power electronic devices [8-10]. To dissipate the high concentrated heat flux, the effective heat spreading capability is quite significant as well. Chemical Vapour Deposition (CVD) diamond heat spreaders are particularly suited for such applications [11-15].

4. Experimental setup

In this work, the enhancement of heat dissipation capability by using the diamond heat spreader in combination with a Silicon-based hybrid micro-cooer has been investigated through experiments and simulations. The fundamental setup is shown in Figure 2. The customized test chip exhibiting eight small hotspots is fabricated, and bonded with Si cooler and diamond heat spreader through thermal compression bonding (TCB) process. The Si hybrid micro-cooler combines the micro-jet impingement array and the micro-channel flow, and can achieve high heat transfer coefficient with low pumping power requirement. The hotspot cooling capability improvement by using the diamond heat spreader is more pronounced for the chip of thickness 100µm. Different types of CVD diamond with thermal conductivities between k>1000W/mK and k>2000W/mK have been attached to the device and compared. The thermal effects of the heat spreader thickness and bonding layer are studied. For GaN device, the dissipated power densities with various cooling solutions are evaluated, while maintaining the peak gate temperature under 200ºC. The consistent results of experiments and simulations have demonstrated the high cooling improvement by using diamond heat spreader on the micro-fluid cooler.

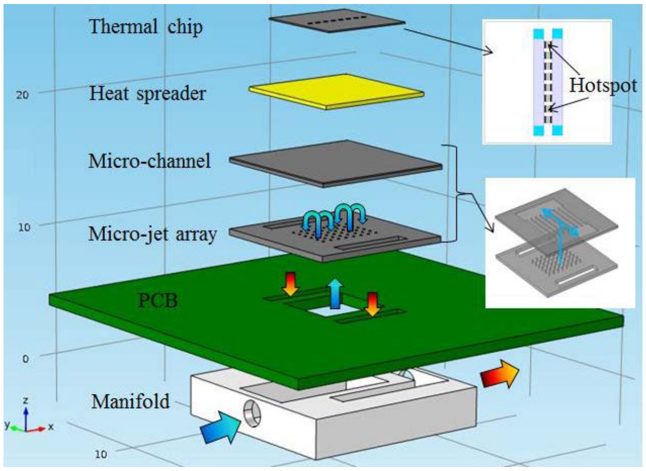

Figure 2: Overview of cooling solution with directly attached diamond between the chip and the micro-cooler.

5. Simulation results

Thermal simulations were performed COMSOL Multi-physics, which 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 3D model, which couples both solid and fluid part. Due to the symmetries in the system, a quarter of the structure with symmetrical boundary conditions is constructed, as is illustrated in Figure 3.

The solution was tested for mesh independency by refining the mesh size. Velocities and temperatures matched within 0.1% for both mesh sizes. The convergence criterion of the solutions is 10^{-6}. The viscous heating feature is considered in the heat transfer interface. The no slip boundary condition is applied for the stationary walls. The natural convection from the topside of the test vehicle is also included. The temperature dependent thermal conductivity of Si is considered, the expressions of which is $k_{Si}=152\times(298/T)^{1.334}$. The thermal conductivity of the applied solder material, Au/Sn material is assumed to be constant, which is 57 W/mK. The Au/Sn bonding layer of 5μm thickness is considered between Si and diamond contact interfaces. The model without and with diamond heat spreader consists of more than 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 small areas of the hotspot heaters.

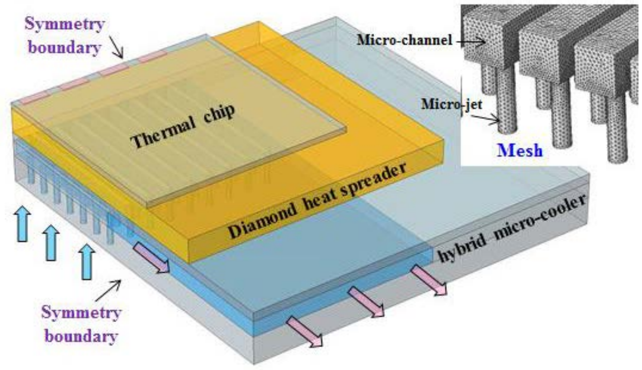

Figure 3: Image of the simulation model (the fluid part is in blue color)

6. Experimental results

The experimental tests are performed on the thermal test chip of 200μm thickness first. The volume flow rate in the micro-cooler is set at 400mL/min, and the pumping power is around 0.2W. The heating power from 10W~100W has been loaded into 8 hotspot heaters (each of size $450\times300\mu m^2$). The steady state simulation is performed with the loading and environment conditions set according to the experimental tests. Within the micro-cooler and its associated flow rate, it is expected to see a laminar flow only. The experimental and simulation results are shown in Figure 4.

Without diamond heat spreader, the structure can dissipate 30W heating power (hotspot heat flux $2.8kW/cm^2$) and 70W ($6.5kW/cm^2$), while maintaining the maximum hotspot temperature under 80ºC and 180ºC, respectively. With the directly-attached diamond heat spreader, the heat dissipation capability can be highly improved. For 54W ($5kW/cm^2$) and 70W ($6.5kW/cm^2$) power dissipation, the maximum hotspot temperature can be reduced by around 25.7% and 26.1% respectively. To maintain the chip temperature under 180˚C, the structure with diamond heat spreader can dissipate around 100W heating power (hotspot heat flux $9.2kW/cm^2$), while without it only around 70W can be dissipated.

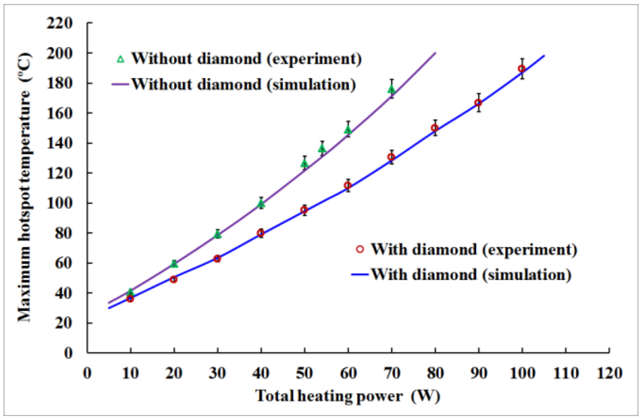

Figure 4: Maximum hotspot temperature as a function of the total heating power for structure with and without Type 1 diamond heat spreader from the experimental tests and simulation analysis

In general, the results from the simulation and the experiments performed match very well. This indicates, that the thermal performance of the structure is accurately simulated. In the hybrid micro-cooler, the spatially average heat transfer coefficient at the top impingement wall in the micro-channel is around $11.3\times10^4 W/m^2K$, 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 Figure 5.

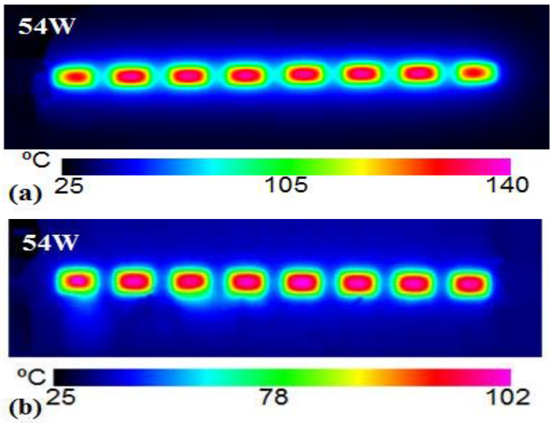

Figure 5: IR camera image of the heating areas in the thermal test chip (a) without and (b) with diamond heat spreader for 54W heating

The maximum temperature occurs at the hotspot located near the Si chip centre, as is shown in Figure 6. For 54W power heating (5kW/cm^2), the maximum temperature of the hotspot located near the chip edge is 8ºC lower than the centre one in the structure without diamond heat spreader. The peak hotspot temperature can be maintained similar by using the diamond heat spreader, which enables 2ºC peak temperature differences between the hotspots located near the edge and the centre.

Above results using Diamond heat spreaders with a room temperature k>2000W/mK were now repeated using a slightly lower k>1500 W/mK. The results show that similar cooling capability has been achieved by using these two types of diamond. To dissipate the same heating power, the maximum hotspot temperature rise by using diamond Type 2 instead of Type 1 is less than 2%, and the increase of the rate α_T is less than 0.4%.

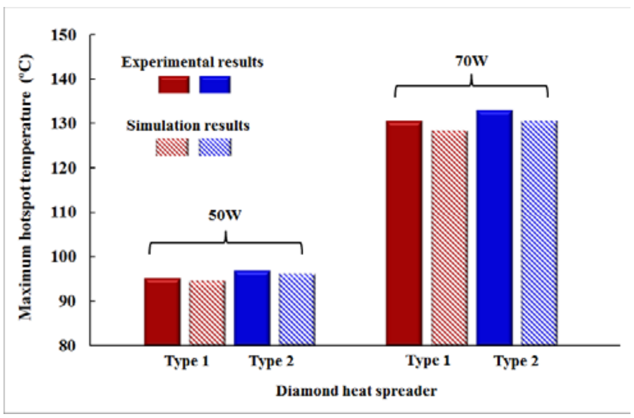

Figure 6: Thermal effect comparison of two types of diamond heat spreader for different heating powers.

Further experimental tests and simulations have been conducted on the thermal test chip of 100µm thickness. This reduced device thickness results in a shorter heat conduction path from the heat source to the cooling solution. The comparison results of the thermal effect are shown in Figure 7.

A more pronounced improvement of the hotspot cooling capability has been achieved by using the diamond heat spreader at k>2000W/mK in this case. Compared with the results in Figure 4, only a slight temperature decrease is enabled by reducing the chip thickness from 200µm to 100µm. For 70W heating, the maximum temperature decreases by less than 2%. However, with smaller thermal resistance between the heat source and the heat spreader, much better heat dissipation capability has been achieved.

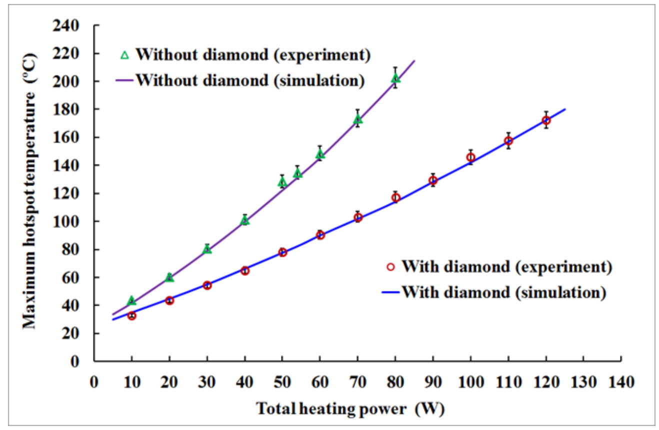

Figure 7: Maximum hotspot temperature as a function of the total heating power for 100µm chip with and without the diamond heat spreader at k>2000W/mK.

With diamond heat spreader, 110W heating power (10.2kW/cm2) can be dissipated, while maintaining the maximum hotspot temperature under 160ºC. To dissipate 70W heating power, the maximum hotspot temperature can be reduced by 40.4% with the diamond heat spreader. The concentrated high heat flux from the small hotspot is effectively reduced for the bottom jet-based micro-cooler to handle. Figure 8 illustrates the heat flux distribution on the top surface of the Si micro-cooler for the structure with and without diamond heat spreader. The improvements realized by applying this highly conductive material is very obvious.

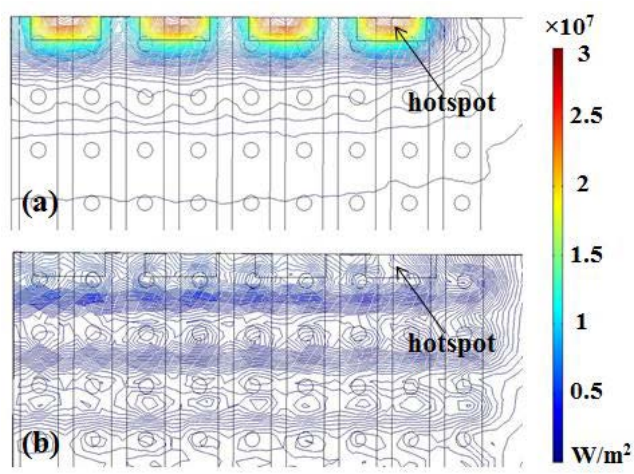

Figure 8: Simulation heat flux distribution on top surface of the Si micro-cooler in the structure (a) without and (b) with diamond heat spreader for 5kW/cm^2 heat flux loading .

Smaller and more uniform heat flux has been enabled by using the diamond heat spreader. The maximum heat flux in Figure 9 (a) is around 2.66kW/cm^2, while that in Figure 9 (b) is only around 0.39kW/cm^2, suggesting the concentrated heat flux has been reduced to 14.7% by using 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 the diamond for the hotspot thermal management.

7. 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 of 100µm thick test chip. The thickness of the heat spreader is changed from 100µm to 700µm. The variations of the maximum hotspot temperature and the maximum heat flux at the top surface of the Si micro-cooler are analysed, as is illustrated in Figure 10.

The diamond heat spreader Type 1 (k>2000 W/mK) is considered 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 400µm thick, and the thermal performance can be slightly improved by increasing the thickness to 700µm. The effect is more sensitive by increasing the thickness from 100µm to 400µm, where the maximum hotspot temperature and the heat flux can be reduced by around 12.1% and 62.3% respectively. The temperature distribution is also affected by changing the heat spreader thickness. For 110W power heating, the peak temperature variation rates α_T of the hotspots are 6.9%, 3.2% and 2.6% for the heat spreader of thickness 100µm, 400µm and 700µm, respectively.

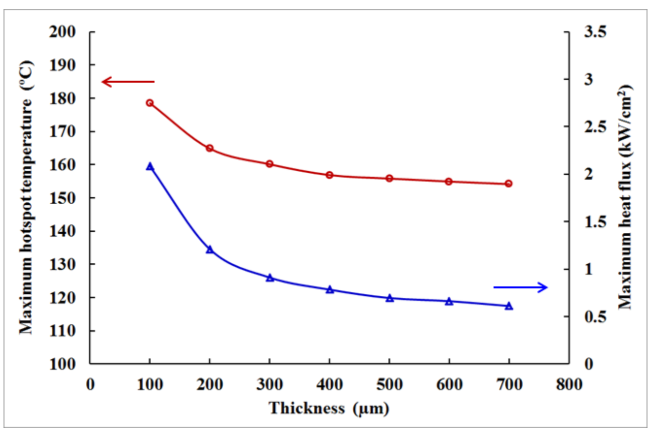

Figure 9: Effect of the Type 1 diamond heat spreader thickness on the thermal performance of the cooling structure for 110W power heating

Four types of diamond heat spreader of different thermal conductivities are analysed and compared in this section. Besides Type 1 and Type 2 mentioned above, Type 3 (thermal conductivity 1800W/mK at 25°C and 1500W/mK at 150 °C) and Type 4 (1000W/mK at 25ºC and 900W/mK at 150 ºC) of the same thickness of 400µm are considered in the simulation comparison shown in Fig.10. The cooling capabilities with Type 1, Type 2 and Type 3 are quite similar. The maximum hotspot temperature rise by changing the heat spreader form Type 1 to Type 4 is around 8%. With Type 4 heat spreader, for 110W power dissipation, the peak temperature variation rates α_T is around 4.9%, which is higher than Type 1 (3.2%) and Type 2 (3.8%). Even so, with Type 4 diamond heat spreader of relatively low thermal conductivity, 110W heat power (hotspot heat flux 10.2kW/cm^2) can be dissipated, while keeping the maximum hotspot temperature under 175ºC.

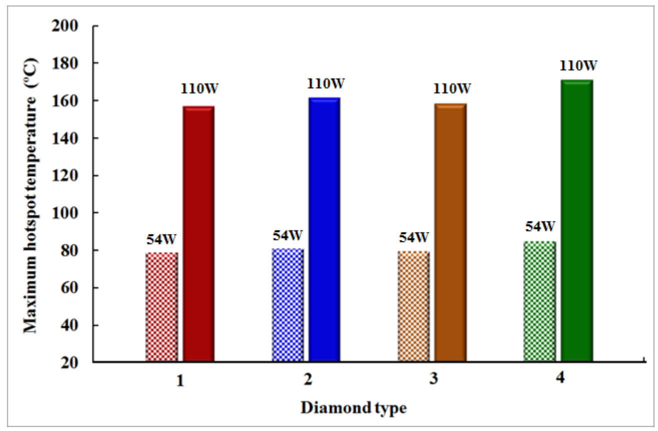

Figure 10: Effect of the heat spreader thermal conductivity on the thermal performance of the cooling structure for different heating powers

There are two bonding layers in the structure with diamond heat spreader, which are quite critical to assure reliable components assembly and low thermal resistance. In the experimental tests, the thickness of both layers is around 5µm.

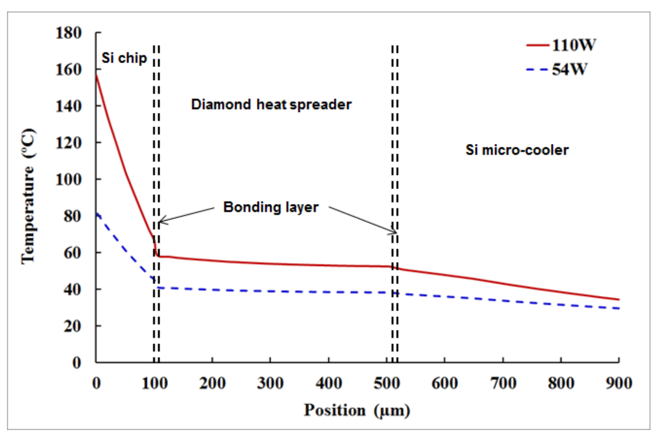

Figure 11: Simulation temperature profile vertically across the structure with diamond heat spreader

Figure 11 shows the temperature profile vertically from the Si chip to the micro-cooler. To dissipate 110W power, the temperature rise caused at the chip-diamond bonding layer is around 8.1ºC, while that at the diamond-cooler bonding layer is negligible. The bonding layer on 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 5μm to 10μm, the temperature rise will increase by 8.8%, and if from 5μm to 20μm, the temperature rise will increase by 12.9%. No obvious temperature increase is observed by just doubling or quadrupling the current thickness of the bonding layer at diamond-cooler interface.

8. Conclusion

Improvement of heat dissipation capability by using the diamond heat spreader on Si hybrid micro-cooler has been investigated for a GaN device. The experimental tests have been conducted on the customized thermal test chip of 8 small hotspots to mimic 8 GaN units. Two types of diamond heat spreader of different thermal conductivities have been used in the test vehicles. Significant improvements of the hotspot cooling capability is been demonstrated by using the diamond heat spreader, especially for the case with thinner thermal test chip. For the chip of thickness 100μm, to dissipate 70W heat power, the maximum hotspot temperature can be reduced by 40.4% with a k>2000 W/mK diamond heat spreader, and 38.1% with k>1500 W/mK diamond material. Using k>2000 W/mK diamond heat spreader, 110W heating power (hotspot heat flux 10.2kW/cm^2) can be dissipated, while maintaining the maximum hotspot temperature under 160ºC. The thermal effects of the heat spreader thickness, diamond thermal conductivity and bonding layer have been analyzed and compared. In the test vehicle, the thin bonding layer of thickness around 5μm has achieved high bonding quality and low thermal resistance. The bonding layer at chip-diamond interface is critical for the thermal performance of the cooling solution. These results confirm, that for modern, very high power (and hence high power density) GaN devices their reliability and performance can be highly improved by effectively spreading the concentrated heat flux from the device into the Si hybrid micro-cooler.

9. References

[1] R. Balmer, B. Bolliger "Integrating Diamond to Maximize Chip Reliability and Performance," in Chip Scale Review, July/August 2013, pp. 26 – 30.

[2] Internal Element Six Technologies research and report.

[3] Y. Mizuno, I. Soga, S. Hirose, O. Tsuboi, and T. Iwai, "Si Microchannel Cooler Integrated with High Power Amplifiers for Base Station of Mobile Communication Systems", ECTC, pp. 1541-1546, 2011.

[4] A. J. Robinson, "A Thermal–Hydraulic Comparison of Liquid Microchannel and Impinging Liquid Jet Array Heat Sinks for High-Power Electronics Cooling," IEEE Trans. Compon. Packag. Technol., vol. 32, no. 2, pp. 347–357, Jun. 2009.

[5] X. Chen, F. N. Donmezer, S. Kumar, and S. Graham,"A Numerical Study on Comparing the Active and Passive Cooling of AlGaN/GaN HEMTs", IEEE Trans. Electron Devices, vol. 61, no. 12, pp. 3152–3158, Dec. 2014.

[6] Y. Han, Y.L. Lee, and , X. Zhang, "Trapezoidal Microchannel Heat Sink With Pressure-Driven and Electro-Osmotic Flows for Microelectronic Cooling", IEEE Trans. on CPMT, vol. 3, no. 11, pp: 1851-1858, 2013.

[7] K. R. Bagnall, Y. S. Muzychka, and E. N. Wang, "Application of the Kirchhoff Transform to Thermal Spreading Problems With Convection Boundary Conditions", IEEE Trans. on CPMT, vol. 4, no. 3, pp: 408-420, 2014.

[8] M. K. Sung and I. Mudawar, "Single-phase Hybrid Micro-channel/ Microjet Impingement Cooling," Int. J. Heat Mass Transf., vol. 51, nos. 17–18, pp. 4342–4352, Aug. 2008.

[9] X. Song, and et al, "Surrogate-Based Analysis and Optimization for the Design of Heat Sinks With Jet Impingement", IEEE Trans. on CPMT, vol. 4, no. 3, pp: 429-437, 2014.

[10] M. Fabbri and V. K. Dhir, "Optimized Heat Transfer for High Power Electronic Cooling Using Arrays of Microjets," J. Heat Transf., vol. 127, no. 7, pp. 760–769, Nov. 2004.

[11] P. Hui and H. S. Tan, "Three-Dimensional Analysis of a Thermal Dissipation System with a Rectangular Diamond Heat Spreader on a Semi-Infinite Copper Heat Sink," Jpn. J. Appl. Phys., vol. 35, no. 9A, pp. 4852–4861,1996.

[12] P. Hui and H. S. Tan, "Temperature Distributions in a Heat Dissipation System Using a Cylindrical Diamond Heat Spreader on a Copper Heat Sink," Jpn. J. Appl. Phys., vol. 75, no. 2, pp. 748–757, 1994.

[13] F. Ejeckam, and et al, "Diamond for Enhanced GaN Device Performance", 14th IEEE ITHERM Conference, pp.1206-1209, 2014

[14] P. Hui, C. P. Tso, and H. S. Tan, "A Rigorous Series Solution for Diamond Heat Spreaders with Temperature-Dependent Thermal Conductivity Used in Microwave Power Devices," Jpn. J. Appl. Phys., vol. 35, no. 11, pp. 5796–5804, 1996.

[15] K. Jagannadham, "Multilayer Diamond Heat Spreaders for Electronic Power Devices," Solid-State Electron, vol. 42, no. 12, pp. 2199–2208, 1998.