SPRING 2016

Electronics COOLING

MARCH 2016
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iNEMI THERMAL MANAGEMENT ROADMAP
What Lies Ahead?

Inside:
Application of Diamond Heat Spreaders on GaN Devices
Enhanced Two-Phase Impingement Technologies
Fairy Tales: Automated Meshing Philosophy
2016 BUYERS' GUIDE

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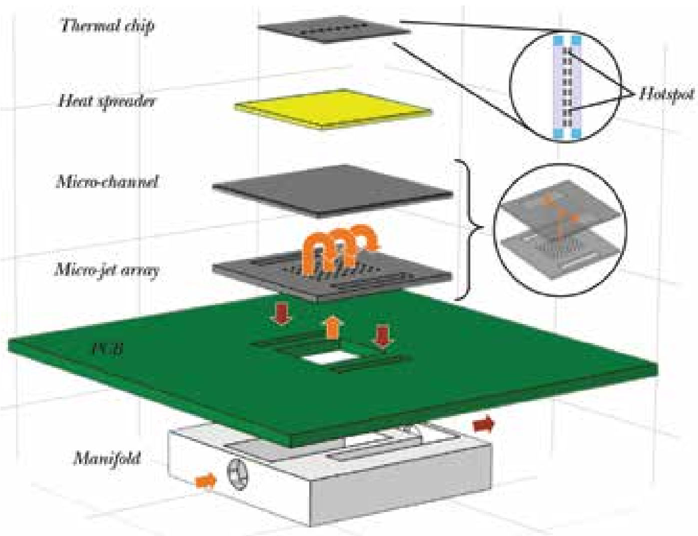
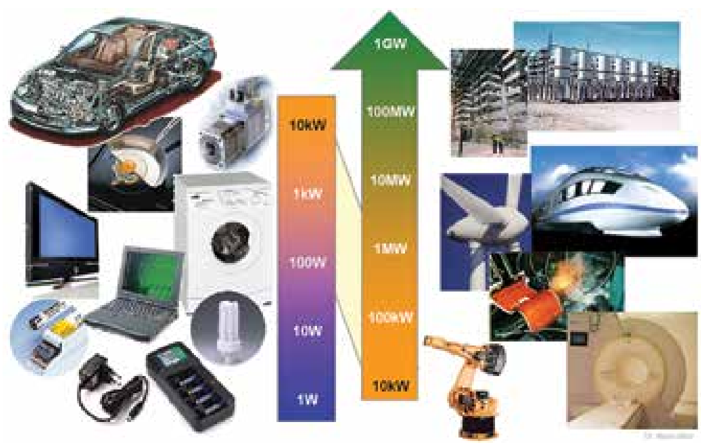


Thermal chip
Heat spreader
Micro-channel
Micro-jet array
PCB
Manifold
Hotspot



1GW
100MW
10MW
1MW
100kW
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10kW
1kW
100W
10W
1W

Editorial 2016

Reflecting on 20 years, and looking to the future

Jim Wilson, Editor-in-Chief, March 2016

***ElectronicsCooling* magazine began in 1995** with a mission: Provide current, practical thermal management information with archival value. We have strived to be editorially independent and provide relevant content that has undergone a technical peer review.

As one would expect, in the past 20 years we have seen changes in the way content is published and archived. Finding an article on the Internet is often the first way people look for information today, and the website for *ElectronicsCooling* continues to attract more and more visitors—while providing a home for archived content. Most of our articles are solicited, which is one reason I have consistently been impressed with the quality of the work presented to our readers.

In this issue, we are privileged to feature an article from the International Electronics Manufacturing Initiative (iNEMI). It presents an overview of the 2015 Roadmap Thermal Management Chapter. I trust this overview will trigger some thoughts related to the current state of electronics thermal management, as well as help identify thermal management needs for the future. Many of us have contributed in the past to these biennial roadmaps, and the finished product reflects the views of a wide range of thermal design engineers.

I would also like to note that this is likely the last time I will have the privilege of communicating with you in this editorial column. I have been blessed to have the opportunity to be a technical editor for the past 12 years, but the time has come for me to allow you the readers to hear some other viewpoints. The responsibilities at my full time job have made it difficult to give the technical editor job the attention it needs and deserves. I intend to stay until a replacement editor is identified.

My first association with this magazine (aside from enjoying the articles) was writing a feature for the Spring 2002 issue titled, "Thermal Issues in GaAs Analog RF Devices." A few readers contacted me with comments and questions and it became evident that this magazine provided a forum for sharing knowledge with peers beyond those you would meet at conferences or technical forums. In 2004 I accepted the role of technical editor and the interaction with our readers has led to many rewarding contacts. I hope to keep these friends as I fully intend to keep working in the electronics cooling field in my day job.

One especially rewarding aspect of serving as editor has been the collaboration with my fellow technical editors (past editors Kavah Azar, Bob Simons, Clemens Lasance, and Madu Iyengar, as well as the current editors Bruce Guenin and Peter Rodgers). I appreciate their insight and coaching. Most important, I consider them all friends. It has also been a pleasure to work with ITEM Media—I have always appreciated their commitment to providing a first-class publication.

To close, I wish to extend personal gratitude to our readers, particularly those who have contributed articles, for your support and willingness to share with others. I am confident that *ElectronicsCooling* will continue to provide value to our readers and I thank you again for this opportunity.

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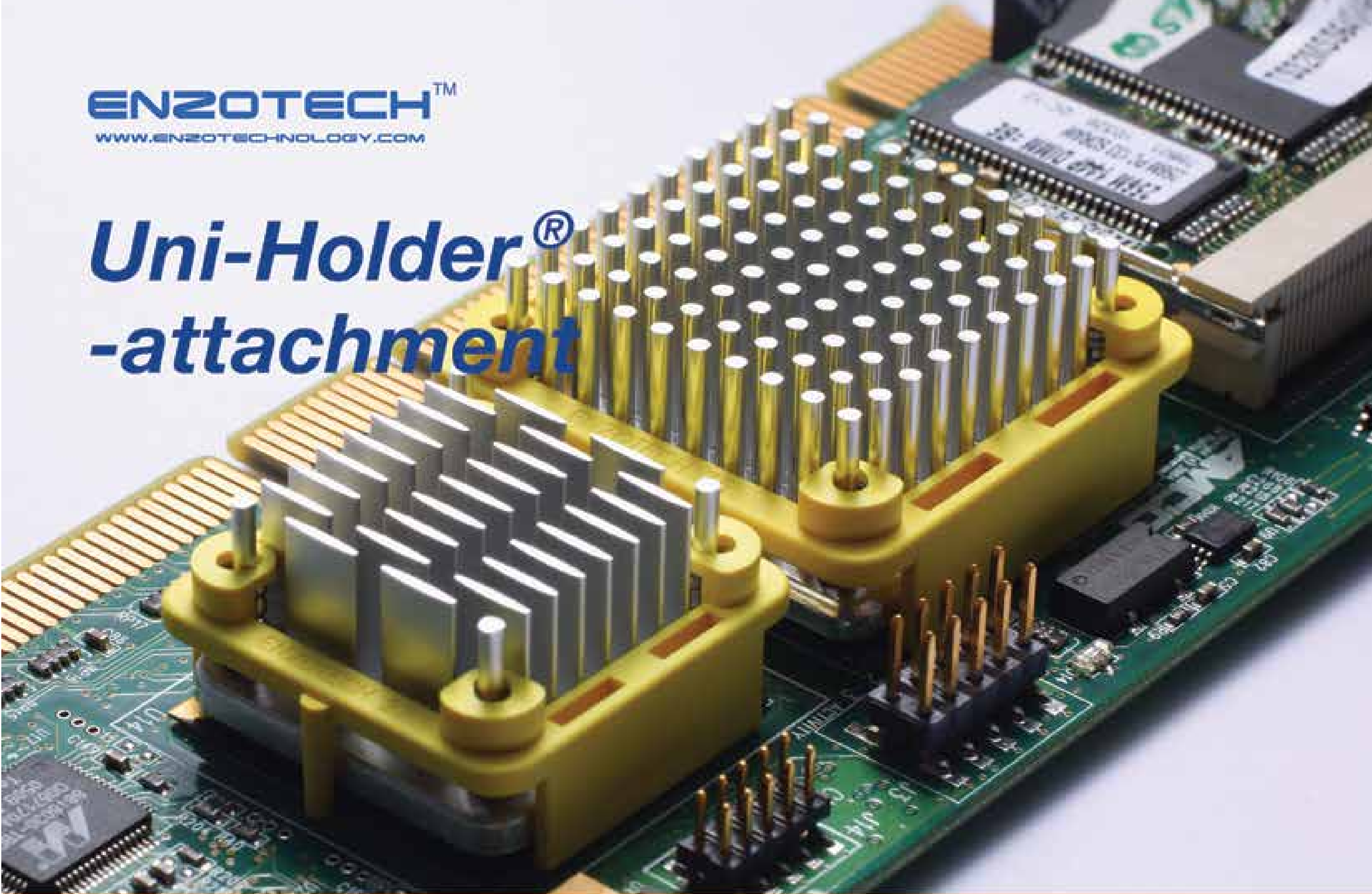

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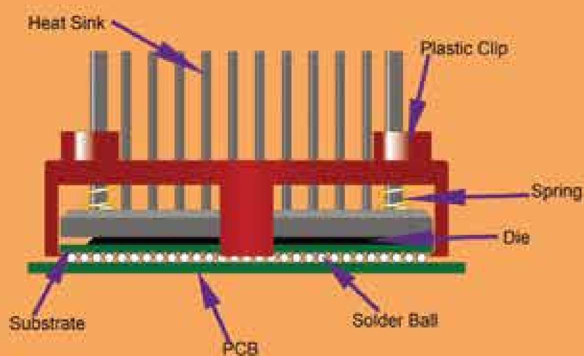

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Cooling Matters

News of thermal management technologies

'KINETIC ENGINE' DESIGN MORE ROBUST FOR CPUs

Startup MIT company CoolChip recently demonstrated a new commercial prototype CPU cooler at CES.

"They've partnered with Cooler Master to release a 'kinetic cooling engine' that can cool a chip 50 percent more efficiently than a conventional cooler, in a form factor that's half the size and emits much less noise," according to Spectrum IEEE.

The initial trigger for the idea came from Sandia Labs, which was working on a new type of CPU cooler called an "air bearing heat exchanger." CoolChip then "invested heavily in technology development beyond the original Sandia Labs concept with high-volume manufacturability, high-volume production pricing, and reliability considerations taken into account," reported Spectrum IEEE.

In addition, Sandia doesn't make commercial products, so CoolChip is taking all the benefits from the design's "more robust cooling, higher efficiency, lower noise, and dust resistance," and putting them on the market, according to Spectrum IEEE.

CoolChip's Kinetic Cooling Engine "should arrive later this year through Cooler Master [and] should be competitive in cost with other CPU cooling systems," according to Spectrum IEEE.

REDESIGNED HEAT SINKS USING 3D PRINTERS

Plunkett Associates has successfully redesigned heat-sinks to improve convection cooling performance using Direct Metal Laser Sintering (DMLS), or 3D printing.

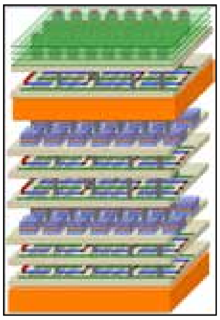
"Each heat-sink was first produced in virtual form and simulated using Computational Fluid Dynamics (CFD) software," reported 3Ders.org.

"The top five heat-sinks were then built by 3T RPD Ltd. using DMLS and physically tested to confirm the accuracy of the virtual tests," according to 3Ders.org.

3Ders.org reports that Plunkett Associates turned to the DMLS process because the "revamped 3D printed components possessed [such] complex internal architectures" they "could not be replicated using other manufacturing processes."

"All five models showed a significant improvement over a standard extruded heat-sink," confirmed 3Ders.org.

'HIGH-RISE' NANO-MATERIALS STACK THERMAL COOLING LAYERS – AND BOOST EFFICIENCY 1000x



Stanford engineers are creating a new approach to the layout of computer processors and memory chips (called Nano-Engineered Computing Systems Technology, or N3XT) – they are stacking processors and memory on top of one another, much like a high-rise architecture.

An engineer's initial thought is this could cause immediate heat problems, but Stanford mechanical engineers Kenneth Goodson and Mehdi Asheghi have a solution.

"Just as skyscrapers have ventilation systems, N3XT high-rise chip designs incorporate thermal cooling layers," reports Phys.org, "This work, [...] ensures that the heat rising from the stacked layers of electronics does not degrade overall system performance."

A working prototype has been demonstrated as "a thousand times more efficient in carrying out many important and highly demanding industrial software applications," according to Phys.org.

Datebook

March 9	March 14 - 17	March 24 - 26	April 12 - 13
Electronics Cooling with Autodesk CFD **Online** http://www.electronics-cooling.com/2016/02/electronics-cooling-with-autodesk-cfd/	**SEMI-THERM 2016** **San Jose, CA, USA** http://www.semi-therm.org/	**The Ninth International Conference on Thermal Engineering Theory and Applications** **Abu Dhabi, UAE** http://www.ictea.ca/	**Data Centre World** **Excel, London, UNITED KINGDOM** http://www.datacentreworld.com/

LEDS CAN DETECT INFRARED HEAT AND TRACK PEOPLE & OBJECTS

Enlighted Inc. is offering LED lighting services that track people and objects by detecting infrared heat.

According to EENews.com, when Enlighted Inc. installs LEDs, it includes next to each LED a tiny disk and antennae packed with a "light sensor, a temperature gauge, a power meter and a motion sensor, as well as wireless devices that communicate with the building-management system, with the other lights and with local smartphones."

"The tracking systems work by means of the sensor modules, installed every 100 square feet with each overhead light," explains Zach Gentry, the vice president of marketing at Enlighted.

Each sensor detects infrared heat and samples 60 times a second to distinguish between a still person and a heater, for example, according to EENews.com. "Meanwhile, the light sensors watch for subtle changes in illumination as light reflects off a passing secretary. Computer servers, hosted in the cloud, stitch the data streams into an image."

Then the system can mesh its data with other systems in the building as well as daylight and weather to "manage light levels," or "pair room occupancy with HVAC data, so the building knows which rooms to heat and cool when," reports EENEws.com.

Enlighted is also considering sticking "coin-sized beacons" on equipment such as company laptops to track where they are in case they get stolen, says EENews.com.

Gentry claims that LEDs not only use less energy than overhead fluorescent tubes, but this upgrade can also "drop the electric bill by 90 percent."

HALF OF NORTH AMERICA UPGRADING DATA CENTER COOLING SYSTEMS

New research by Emerson Network Power recently shows that nearly 50 percent of the United States and Canada have made thermal upgrades to their data center cooling systems.

According to the survey of IT professionals, facility managers and data center managers, "[W]hile 40 percent of data centers have been upgraded in the past five years, nearly 20 percent are in process and about 31 percent will be upgraded in the next 12 months." That's according to ACHRNews.com.

ACHRNews.com stated that the "need for higher equipment reliability, greater energy efficiency, and additional capacity" drove these upgrades.

The Emerson survey found "62 percent of the upgrades are in data centers under 10,000 square feet and 18 percent are in data centers larger than 50,000 square feet," according to ACHRNews.com.

John Peter Valiulis, vice president of thermal management marketing for Emerson Network Power in North America, explained, "As the edge and cloud computing become ubiquitous, ensuring the health of cooling systems at smaller, localized data centers and computer rooms is crucial. Thermal upgrades are allowing companies to improve protection, efficiency, and visibility within all these spaces."

Another finding from the survey was that "40 percent were adding economizers to provide 'free cooling' when outside temperatures allow," according to ACHRNews.com.

INTRODUCING THE WORLD'S FIRST LIQUID-COOLED GAMING LAPTOP

As gaming heats up, Asus ROG has introduced what the company calls the world's first liquid-cooled gaming laptop, the Asus ROG GX700.

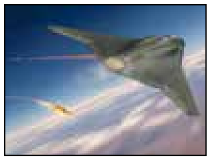
Asus ROG Global Marketing Director Derek Yu created the inch-thick laptop with a Nvidia GTX 980M graphics card and added the cooling system—a "massive, alien-like pod filled with the extra hardware" that plugs right into the laptop, according to TechRadar.com.

The liquid cooling system is split in half to solve a space problem: The GX700 only has a few extra components including "water-channels and water for the coolant to pass through," while the pumps and radiators are found inside a liquid cooling dock, TechRadar.com reports.

Yu explains, "The water cooling section interacts with the existing heat pipes thermal system inside the laptop, so those two work in tandem together. […] But now the water cooling part will take away, [and] offload the heat away from the system toward the radiators [on the dock]."

The laptop has also been equipped with a water-tight seal to prevent spills or leaks.

NEW THERMAL MANAGEMENT TECH DESIGNED INTO FIGHTER PLANE



Northrop Aerospace Systems has released a new artistic concept of a sixth-generation fighter that will combine new technology present in the Lockheed Martin F-22 and B-2 with new thermal management technology.

According to FlightGlobal.com, Northrop president Tom Vice is putting new focus on the quality of managing the heat generated by future weapons and sensors—because designers have overlooked thermal management in the past.

"Northrop's sixth-generation fighter concept shows the stealthy, swept-wing fighter using a powerful laser weapon to engage multiple targets," Vice told FlightGlobal.com. "Even the best high-power lasers are only 32-33% efficient, meaning 2MW of heat is generated for every 1MW of energy that can be formed into a laser beam."

Vice added that "Northrop is pursuing a concept instead that does not rely on accumulators or offboard venting to manage the heat." Such options invite problems like raising the aircraft's visibility and weapon limitations.

Although Northrop is not revealing their exact thermal management plan, FlightGlobal.com reports that "Northrop's concept shows a tailless, possibly supersonic vehicle, promising a new breakthrough in maneuverability, speed and stealth for a combat aircraft," as well as a swept wing.

April 26 - 27

ACIL 2016 Policies and Practices (P2) Conference
Arlington, VA, USA
http://www.acil.org/events/

April 26 - 28

Lightfair International
San Diego, CA, USA
http://www.lightfair.com/

May 31 - June 3

ECTC 2016
Las Vegas, NV, USA
http://www.ectc.net/

ITherm 2016
Las Vegas, NV, USA
http://ieee-itherm.org/

Oct. 4 - 6

Thermal Live 2016
Online
http://www.thermallive2016.com/

Automated Meshing Philosophy?

Peter Rodgers
Associate Technical Editor

FAIRY TALES ARE A WELL-ESTABLISHED way to convey science and technology education. For example, a recent textbook [1] has documented how a range of Victorian-era (1837 – 1901) instructors used fairies and their tales to clarify scientific and technological concepts for young audiences. Today, elementary school curricula continue to incorporate fairy tale-style storytelling to enhance science, technology, engineering and mathematics (STEM) education [2].

Others have adopted a similar approach in the field of electronics-equipment cooling. During the 1990's and early 2000's, Kordyban [3-5] humorously chronicled the myths, mistakes, and "lessons learned" from practicing engineers involved in the field.

In a similar vein, *ElectronicsCooling* initiated the thermal facts and fairy tales (TFFT) column in Spring 2010 [6]. This edition's TFFT is the twenty-fourth column, with all previous columns listed in Table 1. *ElectronicsCooling* has presented these "fairy tales" in an effort to help readers become more efficient in their daily jobs. It is also hoped that these columns have challenged some of your thinking and motivated you to better understand electronics cooling.

This TFFT column continues the theme of previous articles [7,8], documenting challenges encountered in computational fluid dynamics (CFD) modeling of electronics as a virtual prototyping tool.

Responding to the demand for improved design productivity, vendors of CFD codes have significantly enhanced code pre- and post-processing capabilities. One aspect of pre-processing enhancement is automated meshing. However, automated meshing is far from an exact science, as noted by the recent NASA commissioned report on its CFD vision for 2030 [9]. It might be tempting to believe that NASA's 2030 goals for CFD analysis do not apply to electronics cooling. Nevertheless, NASA's report presents a series of seven findings, one of which, Finding 4, states that "*mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow, and very little government investment has been targeted in these areas*" [9].

Generating a high-quality computational mesh for an electronic system is generally one of the most challenging tasks in CFD analysis. The mesh must both represent the geometry and capture the physics of the problem. Consequently, the concept of automated mesh generation is either considered as a dream of the CFD analysts who advocate it, or a fairy tale [10]. Before highlighting areas of caution with automated meshing, it should be noted that meshing is not truly a CFD issue.

The first area of concern for most users is coping with the practical meshing difficulties encountered for real-world CFD applications that have complex geometries (rather than idealized ones, such as flow over a flat plate!). When dealing with actual complex geometries, an automated mesh generator may fail to produce a mesh [11]. Alternatively, the automated mesher may generate a mesh that may not be optimum. Considering that the philosophy of automated meshing is to relieve the user of generating the mesh, the user may feel left with few or no tools for resolving such difficulties.

A second area of concern is that today's meshing software is missing an important element; it has in-built intelligence to understand the geometry/topology of the computation domain, but generally not for understanding the physics of the problem. However, most CFD users expect to obtain reliable simulation results in one round of mesh generation. This is not impossible, but is often not the case. The involvement of the CFD solver is actually required during mesh generation. The typical CFD workflow:

Geometry → Meshing → Physics setup → Solving → Post-processing

may be considered flawed to some extent [12]. In this workflow, meshing is performed before the physical problem setup. Consequently, the meshing software has no information on the physics when generating the mesh, and the CFD solver "expects" a good mesh from its input file.

Table 1: Summary of published Thermal Facts and Fairy Tales (TFFT) columns.

Article Title	Issue	Author*
Most of us live neither in Wind Tunnels nor in the World of Nusselt	Spring 2010	C.L.
Uncertainty is Assured	Summer 2010	J.W.
Fully Developed Channel Flow: Why is Nu Constant?	Fall 2010	C.L.
Fixed Temperature and Infinite Heatsinking	Winter 2010	J.W.
Published Thermal Conductivities Values: Facts or Fairy Tales	March 2011	C.L.
Consistency and Accuracy in Simulations	June 2011	J.W.
Does Your Correlation Have an Imposed Slope?	September 2011	C.L.
Heat Sinks, Heat Exchangers, and History	December 2011	J.W.
Heat Spreading Revisited	March 2012	C.L.
Time Dependent Responses and Superposition	June 2012	J.W.
The Temperature Dependence of the Specific Heat	September 2012	C.L.
Not Always Efficient	December 2012	J.W.
Are Critical Heat Fluxes of LEDs and ICs Comparable	March 2013	C.L.
A System Perspective for Electronics Cooling	June 2013	J.W.
How Useful are Heat Sink Correlations for Design Purposes	September 2013	C.L.
Evolving the Role of the Thermal Engineer from Analyst to Architect	December 2013	Guest Authors
Historical Suggestions for Thermal Management of Electronics	June 2014	J.W.
Virtual Prototyping	September 2014	P.R.
Moist Air and Cooling Electronics	December 2014	J.W.
Past Data and Columns	March 2015	J.W.
The Holy Books of Heat Transfer: Facts or Fairy Tales?	June 2015	C.L.
Numerical Modeling without Supporting Experimentation	September 2015	P.R.
Electronics Cooling Communication for dumMEs and dumEEs	December 2015	J.W.

* Associate technical editor abbreviations: C.L. = Clemens J.M. Lasance; P.R. = Peter Rodgers; and J.W. = Jim Wilson.

Either the CFD software or the user actually needs to understand the physics to ensure that the mesh quality is sufficient to capture the major physics. Unfortunately, meshing software and solver still generally do not communicate with each other directly, except in the case of mesh adaption [10]. The meshing software and solver only communicate through the formatted mesh file/input file. Therefore, to produce a satisfactory mesh, the above CFD workflow actually requires an iterative, trial-and-error procedure. This was not an issue in the past, but may be one today considering the productivity of design analysis requirements. To obtain more reliable predictions, today's users still need to devote time to produce a satisfactory mesh quality, among other requirements, at the expense of a loss in design/analysis productivity. Such an approach ultimately has a cost benefit.

Until the meshing software acquires CFD intelligence - which will imply changes in the conventional CFD workflow - *fully* automated meshing may be considered a fairy tale. Will this change in the near future?

Finally, similarly to the now discontinued technical data columns published from 1997 to 2009 [13], at some point, the list of thermally relevant fairy tales will be exhausted and replaced by a new column topic. We welcome our readers' inputs in suggesting new column topics.

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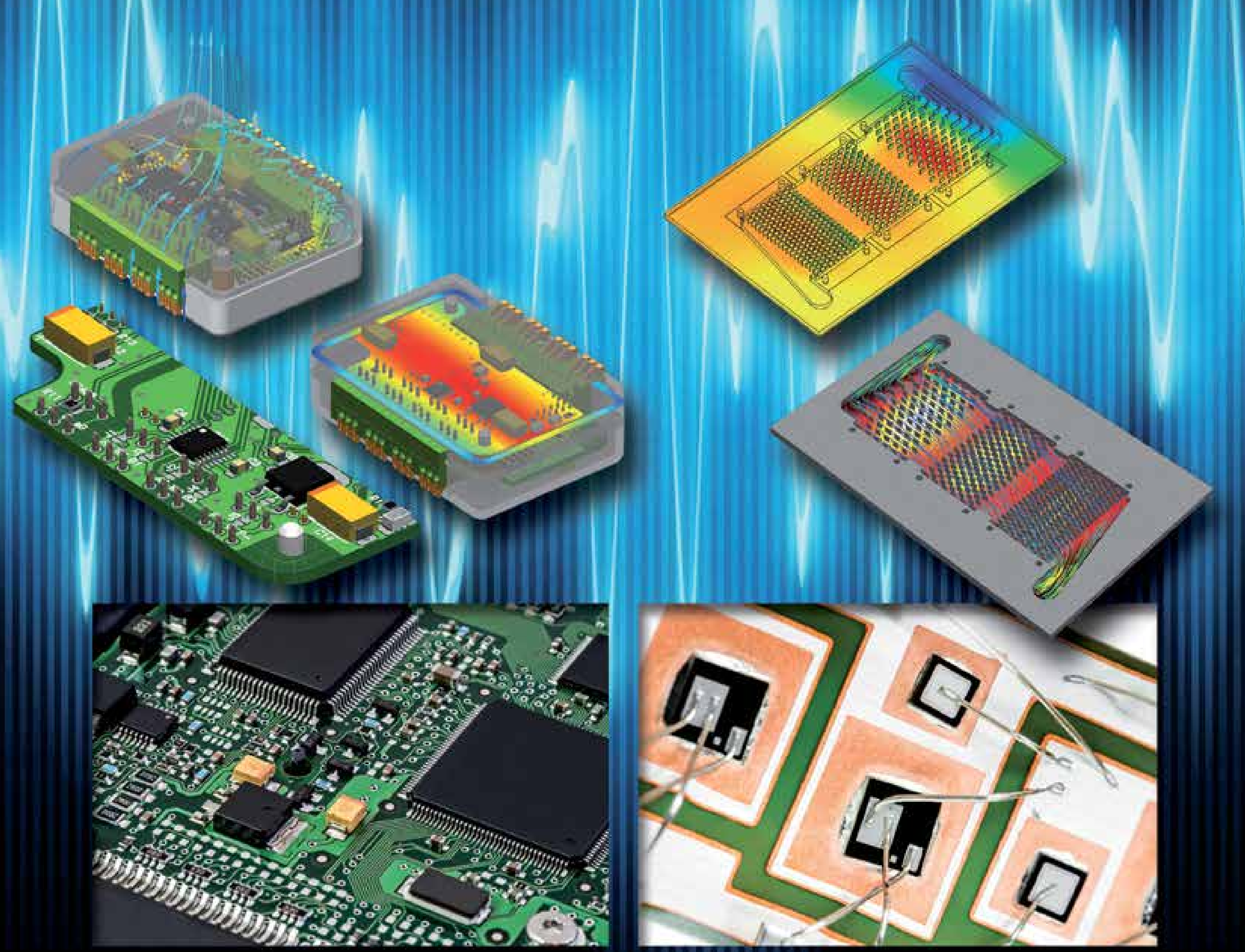

Estimating Parallel Plate-fin Heat Sink Pressure Drop

Robert E. Simons
IBM Corporation (Retired)

Editor's note: In recognition of the 20th year of ElectronicsCooling, we are republishing articles from past issues that we believe to be of particular value to our readership. The following article was published in the May 2003 issue as a Calculation Corner authored by Bob Simons. It is the sequel to the companion article, "Estimating Parallel Plate-Fin Heat Sink Thermal Resistance," originally published in February 2003 and reprinted in the December 2015 issue.

Bob served as an Associate Technical Editor of this publication from January 2001 to December 2011. For those readers who find this sort of tutorial useful, please refer to the list compiled by Bob of other Calculation Corner columns authored by him as well as by others: http://www.electronics-cooling.com/2011/09/a-useful-catalog-of-calculation-corner-articles/.

IN THE LAST ISSUE OF *ElectronicsCooling* a methodology was presented for estimating parallel plate-fin heat sink thermal resistance [1]. The method presented assumes that the air flow rate is given, either in terms of the average velocity, V, between the fins or a volumetric flow rate, G. Although this methodology was shown to be useful in examining the effects of heat sink geometry on heat sink thermal resistance over a range of air flow rates, it cannot be used by itself to predict the performance of a given heat sink design in a particular application. To do this it is necessary to know the actual air flow rate that will be delivered through the heat sink by the fan or blower to be used in the application. To determine the air flow rate it is necessary to estimate the heat sink pressure drop as a function of flow rate and match it to a curve of fan pressure drop versus flow rate. A method to do this, using equations presented in a paper by Culham and Muzychka [2], will be discussed in this article. As in the previous article, the heat sink geometry and nomenclature used is that shown Figure 1.

The pressure drop across the heat sink, ΔP, is given by:

$$\Delta P = \left(K_c + 4 \cdot f_{app} \cdot \frac{L}{D_h} + K_e \right) \cdot \rho \frac{V^2}{2} \quad (1)$$

where: L = Length of the heat sink channels in the flow direction D_h = Hydraulic diameter of the flow channels, ρ = Air density, and V = Average velocity of air flowing through the channels.

The hydraulic diameter, D_h, is approximately equal to 2b, where b is the gap between the fins given by:

$$b = \frac{W - N_{fin} \cdot t_f}{N_{fin} - 1} \quad (2)$$

where: N_{fin} = Number of fins, t_f = Fin thickness, and W = Heat sink width.

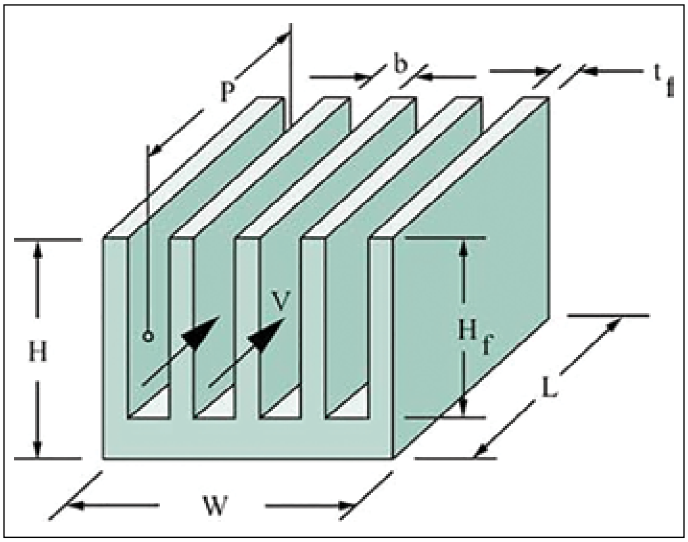

Figure 1. Parallel plate fin heat sink configuration.

The coefficients K_c and K_e represent the pressure losses due to the sudden contraction and expansion of the flow entering and leaving the heat sink flow channels between the fins. These coefficients may be determined using:

$$K_c = 0.42 \cdot \left(1 - \sigma^2\right) \quad (3)$$

and

$$K_e = \left(1 - \sigma^2\right)^2 \quad (4)$$

where σ = the ratio of the area of the flow channels to that of the flow approaching the heat sink, and is given by:

$$\sigma = 1 - \frac{N_{\text{fin}} \cdot t_{\text{f}}}{W} \quad (5)$$

The average velocity for use in Equation (1) is related to the volumetric air flow rate, G, by:

$$V = \frac{G}{N_{\text{fin}} \cdot b \cdot H_{\text{f}}} \quad (6)$$

where H_f = fin height.

The apparent friction factor, f_{app}, for hydrodynamically developing laminar flow is related to the friction factor, f, for fully developed flow and may be calculated from:

$$\text{f}_{\text{app}} = \frac{\left[\left(\frac{3.44}{\sqrt{L^*}}\right)^2 + \left(\text{f} \cdot \text{Re}\right)^2\right]^{1/2}}{\text{Re}} \quad (7)$$

where L^* is given by:

$$L^* = \frac{L/D_h}{\text{Re}} \quad (8)$$

and the Reynolds number, Re, is given by:

$$\text{Re} = \frac{\rho \cdot V \cdot D_h}{\mu} \quad (9)$$

where μ = dynamic viscosity of air.

The friction factor for fully developed laminar flow used in Equation (1) is a function of both the aspect ratio, λ (where $\lambda = b/H_f$), of the heat sink flow channels and the Reynolds number as given by:

$$\text{f} = \left(24 - 32.527 \cdot \lambda + 46.721 \cdot \lambda^2 - 40.829 \cdot \lambda^3 + 22.954 \cdot \lambda^4 - 6.089 \cdot \lambda^5\right) / \text{Re} \quad (10)$$

Using the preceding equations and Equation (1) with air velocity in m/s and air density in kg/m^3 will give the overall pressure drop across the heat sink in Pascals (1 Pascal = 0.00401 in. of H_2O).

For purposes of illustration, these equations were used to estimate the pressure drop across a heat sink of the same dimensions as that considered in the earlier article. That is a 50 x 50 mm heat sink with 10 to 30 fins, 0.5 mm thick and ranging in height from 12.5 to 50 mm. The pressure drop for each heat sink configuration was calculated for volumetric air flow rates ranging from 0 to 10 CFM (0.00472 m^3/s). These results are shown in Figure 2.

At a given volumetric air flow rate those heat sinks with more fins and shorter fins experience a higher air velocity in the heat sink channels and exhibit a higher pressure drop. At the same volumetric air flow rate those with fewer fins and taller fins experience a lower air velocity in the heat sink channels and exhibit a lower pressure drop. Also shown in Figure 2 is the fan curve for a typical fan that might be used to provide air flow for the heat sinks under consideration. The intersection of the fan curve with the flow impedance curve for any heat sink determines the flow the fan will deliver to that heat sink. As may be seen in the figure, when used with a heat sink with 10 fins, 12.5 mm tall, the fan will deliver 4.1 CFM (0.0019 m^3/s).

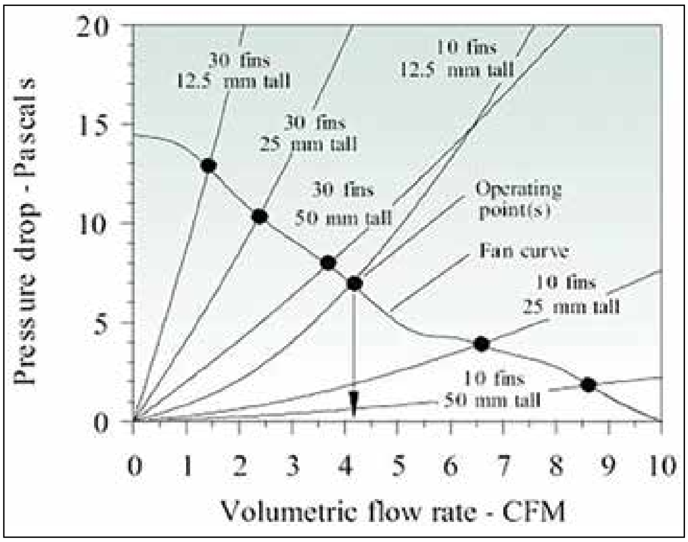

Figure 2. Heat sink pressure drop curves and fan curve with flow operating points.

Figure 3 shows the flow that the fan will deliver to each of the heat sink configurations, depending upon the number of fins and the height of the fins. Using the flow rate for each heat sink configuration and the methodology described in the earlier article [1] the corresponding heat sink thermal resistance was calculated for each heat sink to obtain the results shown in Figure 4. These results clearly show that for each configuration a minimum heat sink thermal resistance is achieved with 23 fins and that there is little benefit in using a fin height greater than about 37 mm.

Of course, if a fan with a different fan curve is employed, the flow rates will change and the optimum heat sink design point may change as well. The important point is that to determine how a heat sink will perform in a given application both its heat transfer and pressure drop characteristics must be considered in concert with the pressure-flow characteristics of the fan that will be used.

It should also be noted that an underlying assumption for both this article and its predecessor is that all the flow delivered by the fan is forced to go through the channels formed between the heat sink fins. Unfortunately, this is often not the case and much of the air flow delivered by the fan will take the flow path of least resistance bypassing the heat sink. Under such circumstances the amount of flow bypass must be estimated in order to determine the heat sink performance. An approach to estimate heat sink air flow bypass may be found in an article by Simons and Schmidt [3].

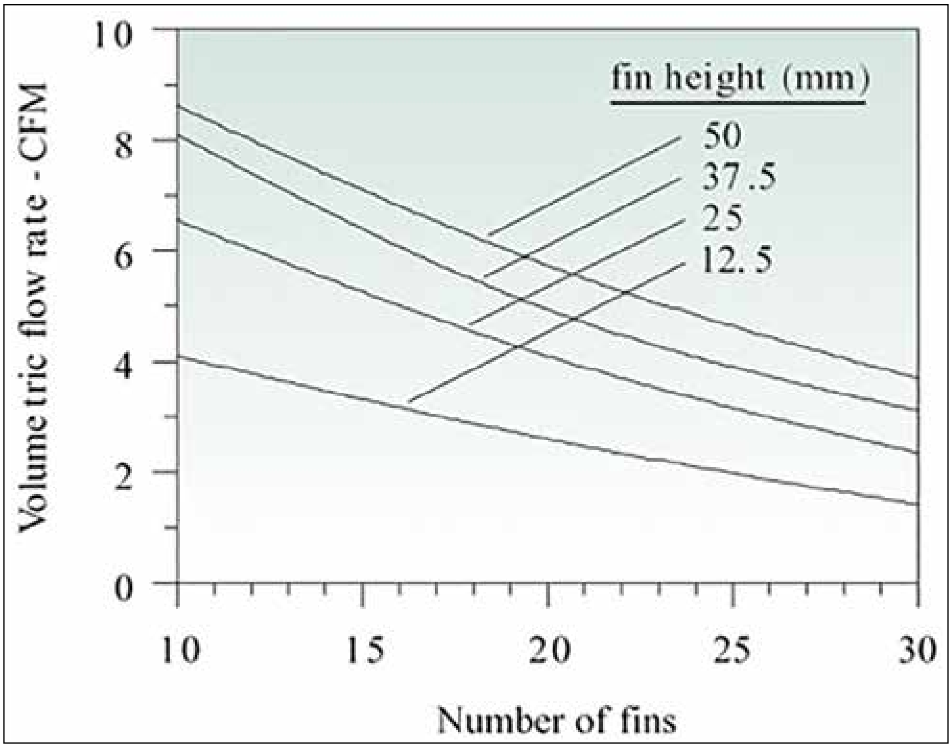

Figure 3. Effect of number of fins and fin height on volumetric air flow rate through heat sink.

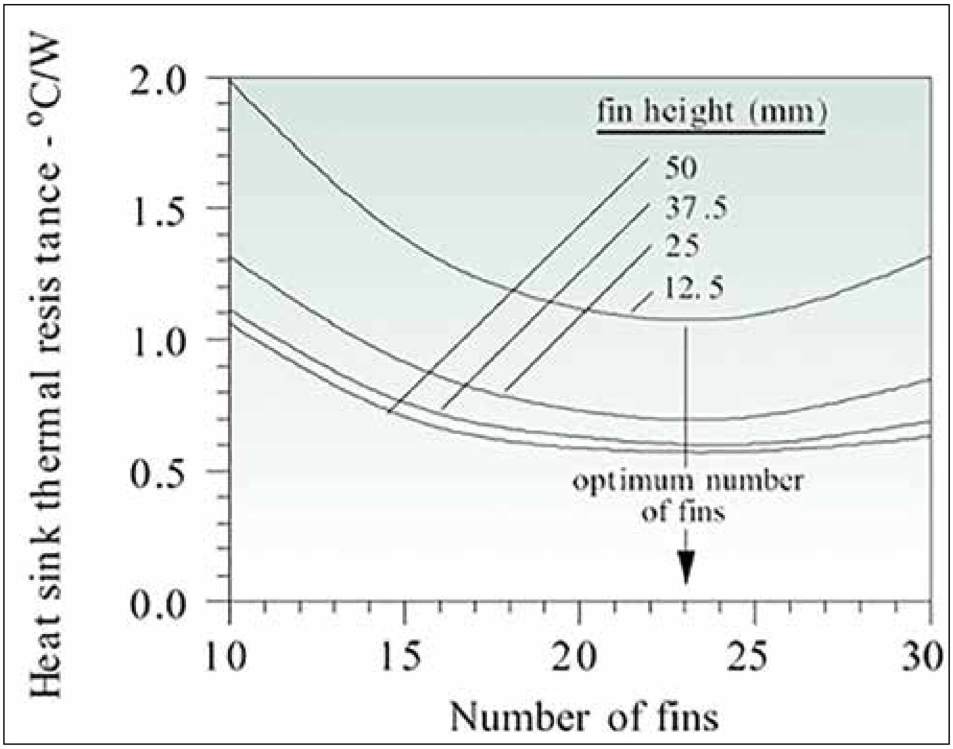

Figure 4. Effect of number of fins and fin height on heat sink thermal resistance.

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Enhanced Two-Phase Impingement Technologies for Electronics Cooling

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INTRODUCTION

THE COOLING DEMANDS OF MODERN electronics are fast approaching the practical limits of single-phase cooling technologies. As heat fluxes increase, the heat transfer coefficients necessary for electronics thermal management are becoming difficult to attain purely through single-phase convection. The requirement to use dielectric liquids instead of water only exacerbates this challenge to cool electronics, because of water's more favorable thermal properties.

One potential solution has been boiling heat transfer, which has attracted much attention as a method to efficiently dissipate high heat fluxes with dielectric liquids; however, the addition of a vapor-phase to a liquid flow is generally accompanied by a large increase in pressure drop. A rise in pressure drop increases the overall pumping power necessary to drive the cooling loop, increasing the parasitic power consumption of the cooling system. Furthermore, the high pressure head necessary to feed a high-pressure-drop heat sink can increase strain on the pump, tubing, and other hardware in the cooling system, decreasing reliability and longevity. A need still exists for a cooling technology that can both dissipate the high heat fluxes of modern electronics while providing low-pressure-drop pumping characteristics.

Two-phase jet impingement is a promising technology for achieving high heat removal rates at moderate pressure losses. In two-phase jet impingement, one or more jets impinge liquid onto a heated surface, where it boils. This cooling approach can achieve high-heat transfer coefficients in both single- and two-phase operation —with an enhanced critical heat flux (CHF) compared to pool boiling [1]. Because the liquid/vapor mixture has a relatively large outflow path compared to channel

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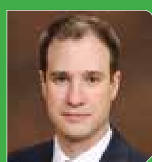

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geometries, vapor generation only causes minimal pressure drop increases [2]. These characteristics make two-phase jet impingement an attractive starting point for the development of a low-pressure-drop heat sink for electronics cooling applications.

Surface enhancements can augment the heat transfer coefficients on boiling surfaces and increase CHF [3]. Their combination with two-phase jet impingement can greatly augment heat transfer coefficients [4]; however, surface enhancement design for boiling with jet impingement is by no means straight forward. It is important to position surface enhancement structures to enhance boiling heat transfer, while also causing minimal increases in pressure drop through the heat sink. Impinging jets serve to locally enhance convective heat transfer and to actively supply liquid to the boiling surface. Engineers can use knowledge of the local interactions between the impingement from the liquid jets and boiling on the surface to design complementary surfaces for maximum effectiveness.

SURFACE ENHANCEMENT DESIGN FOR TWO-PHASE JET IMPINGEMENT

Infrared imagery of thin-foil heat sources is one method to obtain information about the local heat transfer interactions for the design of surface enhancement structures [2]. The local heat transfer coefficient from an array of 25 jets of HFE-7100 [5] impinging on a smooth surface undergoing boiling is shown in Figure 1b. Liquid flowing through orifices in a flat plate, as shown in Figure 1a, form the impinging jets. This experimental heat transfer coefficient map shows the simultaneous occurrence of both single- and two-phase heat transfer on the heated surface. The jet stagnation regions, located directly beneath the impinging jets, remain dominated by the single-phase convection provided by the liquid impingement. Boiling occurs primarily between the jets and is evident through the small-scale randomness in the contours of heat transfer coefficient. Boiling surface enhancement structures are most beneficial in these inter-jet areas.

A surface enhancement using pin fins coated with a porous layer is shown in Figure 2. This surface both provides ample surface area enhancement (3-fold compared to a flat surface without the pin fins) and promotes enhanced boiling through the application of a porous boiling enhancement coating [7,8], shown in the SEMs in Figure 2b. The fins, 0.5 mm in width, 2.5 mm in height, and spaced 1.5 mm apart, are positioned between the impinging jets to provide boiling enhancement in these regions and to minimally disrupt the impinging liquid flow. The resulting liquid flow paths are largely unobstructed through the heat sink as shown in Figure 2a. The surface shown in Figure 2 has a 25.4 mm square base area to simulate the size of a large-area electronics device.

ENHANCED HEAT TRANSFER AND PUMPING POWER RESULTS

The surface enhancement combined with the impinging jets drastically improves the heat transfer characteristics achievable with this flow geometry, as shown in Figure 3. In this figure, the effective heat transfer coefficient is defined as

$$h = \frac{q}{A_{base}\left(T_{jet} - T_s\right)} \quad (1)$$

where q [W] is the heat input (after accounting for heat losses), A_{base} [m^2] is the projected area of the base of the heat sink, T_{jet} [K] is the jet temperature (the jet inlet temperature is subcooled 10 °C below the saturation temperature, 61°C), and T_s [K] is the average base surface temperature.

Compared to a plain copper surface, the coated pin-fin surface drastically increases the heat transfer coefficients and also extends the operating range by delaying critical heat flux (CHF). The enhancement with the impinging jets achieves an effective heat transfer coefficient of h = 52,100 W/m^{2}K at a heat flux of q'' = 126.9 W/cm^2 at a flow rate of 1800 ml/min. The plain copper surface only reaches h = 13,800 W/m^{2}K at a much lower heat flux of 50.2 W/cm^2 at this flow rate. The increase in CHF because of the surface enhancement is also drastic; a 4-fold increase in CHF is observed at all flow rates—with a maximum heat flux of 205.8 W/cm^2 achieved at 1800 ml/min.

The favorable heat transfer performance presented above only satisfies part of the challenge in cooling electronics devices. The low pumping power characteristics of two-phase

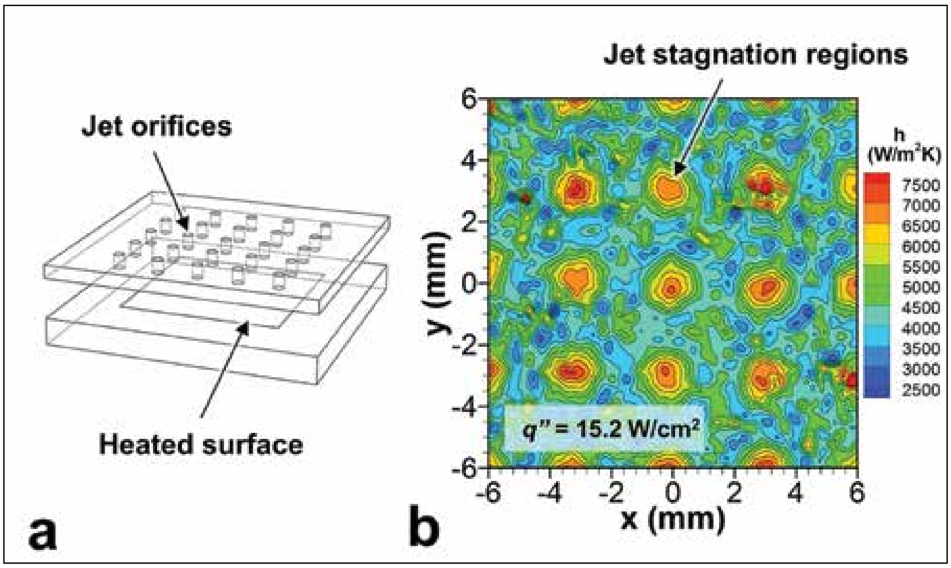

Figure 1. (a) A schematic diagram of the 5 × 5 array of jet orifices positioned over a smooth flat surface, and (b) the local heat transfer distribution during boiling and liquid impingement from the jet array. The central jet in the array impinges at x = 0 and y = 0 mm.

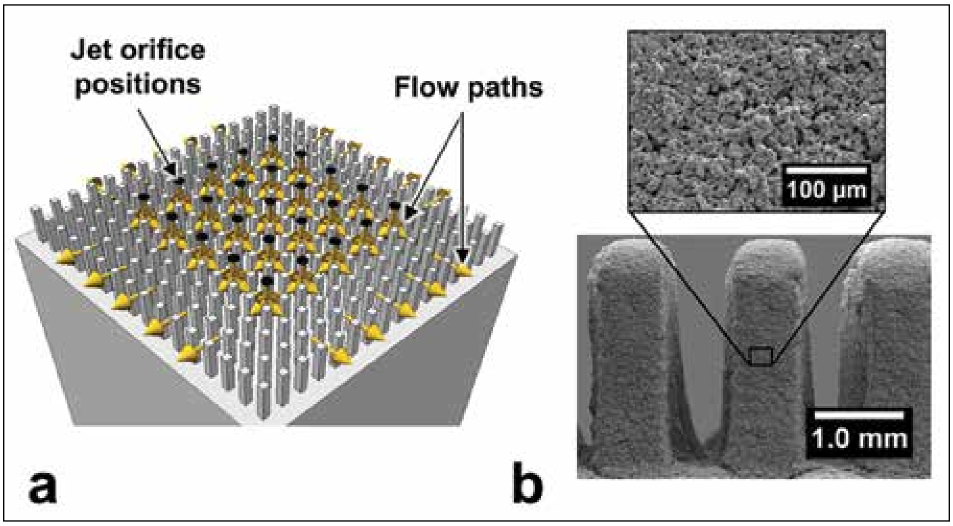

Figure 2. The complementary surface enhancement shown as: (a) a 3D drawing with the liquid impingement and outflow paths, and (b) SEM images of the porous coating and pin fins after coating [4,6].

jet impingement are what set it apart from other two-phase cooling technologies. Plotted in Figure 4 is the pumping power (P_{pump}) for each flow rate measured at CHF. This value represents the highest pumping power measured for each flow rate, as lower heat input resulted in less vapor generation and a lower pressure drop at a given flow rate. Plotted on a semi-log axis, the pumping power is shown to increase linearly with the CHF limit. An exponential fit to the data of the form

$$P_{pump} \propto e^{\gamma q''_{CHF}} \quad (2)$$

reveals that the fitting constant, γ, for the coated pin-fin surface ($\gamma = 0.04$) is an order of magnitude lower than that of the plain copper surface ($\gamma = 0.17$). The lower constant indicates that the jet array with the coated pin-fin surface can dissipate much larger heat fluxes with only small penalties in pumping power compared to what is needed when using the smooth surface. For example, the pumping power necessary to reach $q''_{CHF} = 100$ W/cm^2 with the plain copper surface would be multiple orders of magnitude higher than that necessary with the coated pin fin surface at the same heat flux, given the trends presented in Figure 4. The pressure drop component of the pumping power for each point is also listed in Figure 4. A maximum pressure drop of 10.9 kPa is observed, illustrating that only a small pressure head is necessary with this two-phase heat sink.

CONCLUSIONS AND FUTURE WORK

Knowledge of the local interactions between impinging liquid jets and boiling can greatly aid in the design of surface enhancement structures. Obtaining this knowledge through local heat transfer measurements is an effective tool for electronics thermal management. The present results show that the coated pin fins complement the flow from the impinging jet array, resulting in low-pumping-power characteristics and greatly enhanced cooling capabilities with dielectric liquids. Further analysis combining local heat transfer measurements with CFD studies [9] might provide additional avenues for the design of complementary surface enhancements for non-traditional jet shapes. This design strategy might yield ultimate control over the heat flux dissipation and local heat transfer distributions achievable at a set pumping power with two-phase jet impingement cooling.

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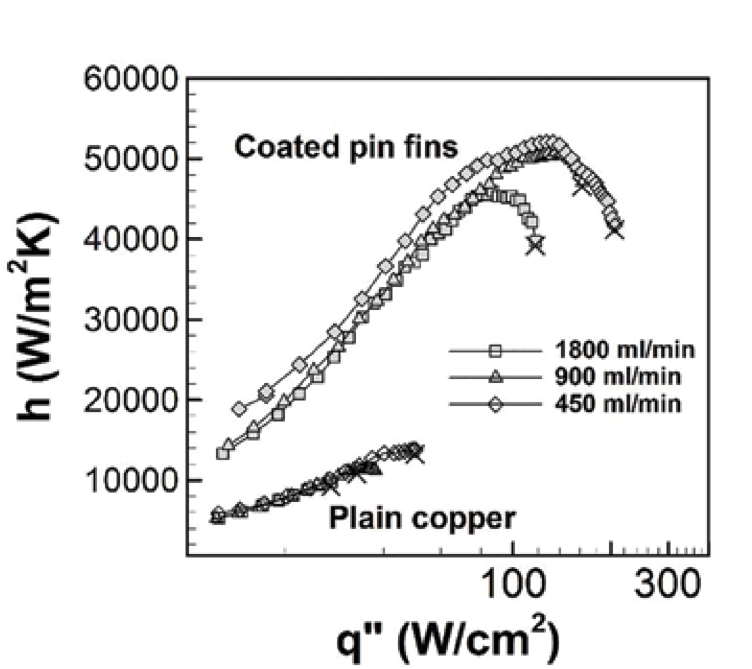
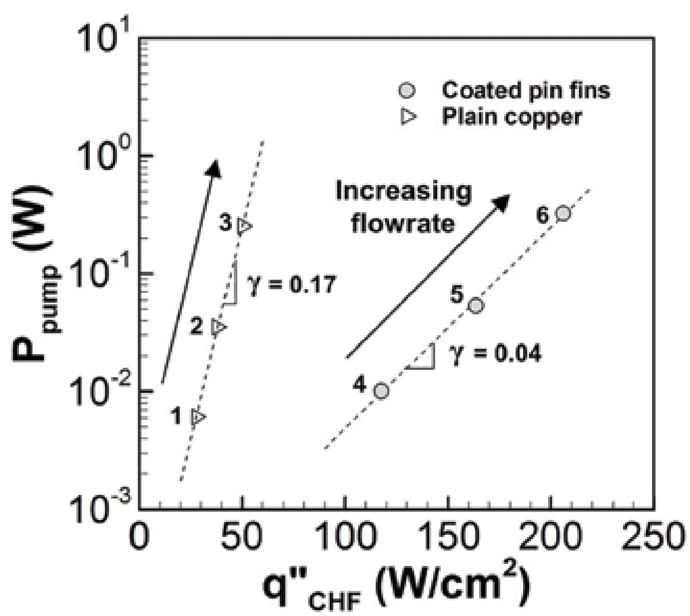


Figure 3. Effective heat transfer coefficients as a function of heat flux for the coated pin-fin surface and plain copper surface at three volumetric flow rates. CHF for each case is denoted by the symbol ×.



	Flow rate (ml/min)	ΔP (kPa)	q''_{CHF} (W/cm^2)
1	450	0.8	27.7
2	900	2.4	37.8
3	1800	8.5	50.2
4	450	1.4	117.4
5	900	3.6	163.4
6	1800	10.9	205.8

Figure 4. (LEFT) Pumping power at CHF and (RIGHT) the pressure drop measured at CHF for each flow rate.

Application of Diamond Heat Spreaders for the Thermal Management of GaN Devices

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1. INTRODUCTION

AS DEVICES BECOME SMALLER, THEY still require high reliability in the presence of extreme power densities (greater than 1 kW/cm^2). This creates demand for new thermal management solutions. Nowhere is this more evident than with the use of gallium nitride (GaN) transistors, where engineers struggle with thermal barriers that limit 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 chemical vapor deposition (CVD) diamond heat spreaders [1].

GaN-based transistors and their related radio frequency (RF) power amplifiers (PAs) have emerged as the leading solid-state technology to replace traveling wave tubes in radar, electronic warfare (EW) systems and satellite communications. However, the operation of GaN high electron mobility transistors (HEMTs) on silicon chips poses a significant challenge to thermal management, as the heat generation is concentrated in very small areas, typically measured in microns. The gate-to-gate spacing in typical GaN HEMT devices is typically less than 50 µm. This leads to significant thermal gradients and high operating temperatures, which can affect device performance and endurance. Elevated temperatures adversely impact reliability. As a consequence, effective thermal management is essential for the GaN device and is important to reach its full potential [2]. As found in previous studies, both micro-channel and micro-jet heat sinks can dissipate high heat fluxes anticipated in high power electronic devices [3]. Dissipating the high concentrated heat flux requires an effective heat spreading capability. CVD diamond heat spreaders are particularly suited for such applications [4].

This article assesses the thermal performance of CVD diamond heat spreaders for a hybrid silicon micro-cooler used 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 thermal compression bonding (TCB) process to a silicon thermal test chip designed to mimic the hotspots of eight GaN devices. The heat dissipation capabilities are compared through experimental tests and numerical simulations. It is hoped that the findings presented in this article can highlight the potential effectiveness of CVD diamond heat spreaders, utilized in a number of different configurations, for the thermal management of GaN devices.

2. CVD DIAMOND

Diamond possesses an extraordinary set of properties, including: the highest known thermal conductivity, stiffness and hardness; high optical transmission across a wide wavelength range; low thermal expansion coefficient; and low density. These characteristics can make diamond a material of choice for thermal management to significantly reduce thermal resistance in a variety of applications. CVD diamond is now readily commercially available in different grades with thermal conductivities ranging from 1000 W/m-K to 2000 W/m-K. CVD diamond also has fully isotropic characteristics, enabling enhanced heat spreading in all directions.

Ongoing development in the technologies to synthesize CVD diamond has enabled this material to become readily available in volume costs of approximately \$1/mm^3. In some instances, diamond heat spreaders enable system operation at elevated temperatures, enhance the heat removal capability and reduce the overall system cost. When applied with appropriate die-attach methods, diamond heat spreaders provide reliable solutions for semiconductor packages with significant thermal management challenges [2].

Thomas Obeloer is a business development manager at Element Six Technologies (Santa Clara, CA) and works on thermal management and optical applications of CVD Diamond. He holds a master's degree in mechanical engineering from Hanover University (Germany) and has more than 20 years experience in manufacturing, process engineering and business development. For the last 15 years, he has been involved in sales and marketing activities for advanced thermal management, mainly in the field of advanced materials, such as high-performance ceramics, CVD Diamond and Diamond composites.

3. EXPERIMENTAL SETUP

Experiments and simulations will demonstrate the enhancement of heat dissipation capabilities of using CVD diamond heat spreaders in combination with a silicon-based hybrid micro-cooler. Figure 1 shows the experimental setup. A customized test chip exhibiting eight small hotspots was fabricated and bonded to both the silicon cooler and diamond heat spreader through a thermal compression bonding (TCB) process. The silicon hybrid micro-cooler combines micro-jet impingement and micro-channel flow. Different types of CVD diamond material with thermal conductivities of 1500 W/m-K and 2000 W/m-K were attached to the device and their performance compared. Also studied was the thermal effect of both the heat spreader and bonding layer thickness. For the simulated GaN device, the dissipated power densities for various cooling solutions were evaluated.

The experimental tests were performed on the thermal test chip of 200µm thickness. The chip heating power ranged from 10W to 100W generated by the eight hotspot heaters (each of size 450 × 300µm²). The micro-cooler flow rate was 400 ml/min requiring a pumping power of 0.2W.

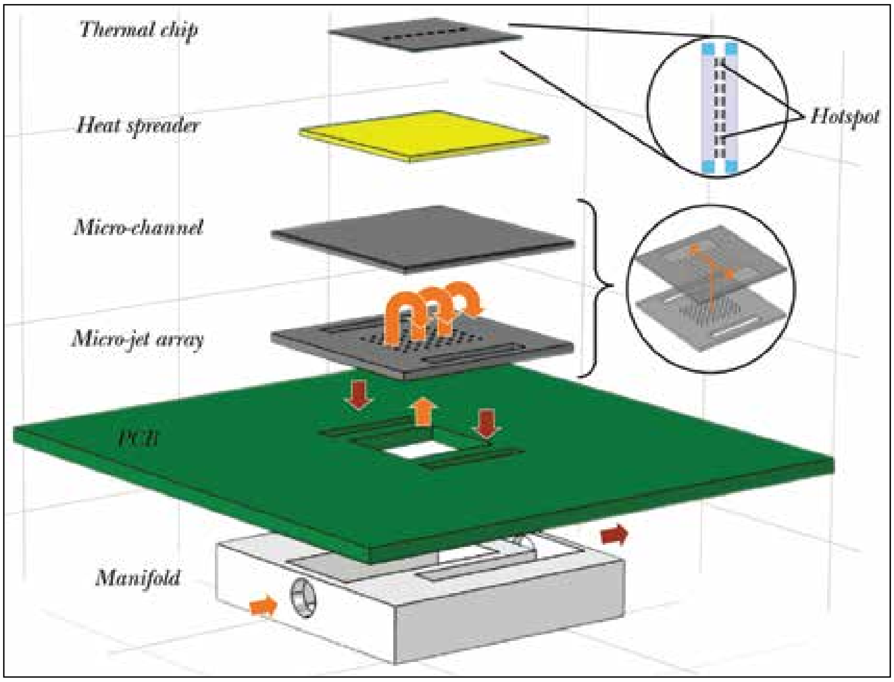

Figure 1: Schematic representation of the experimental set-up.

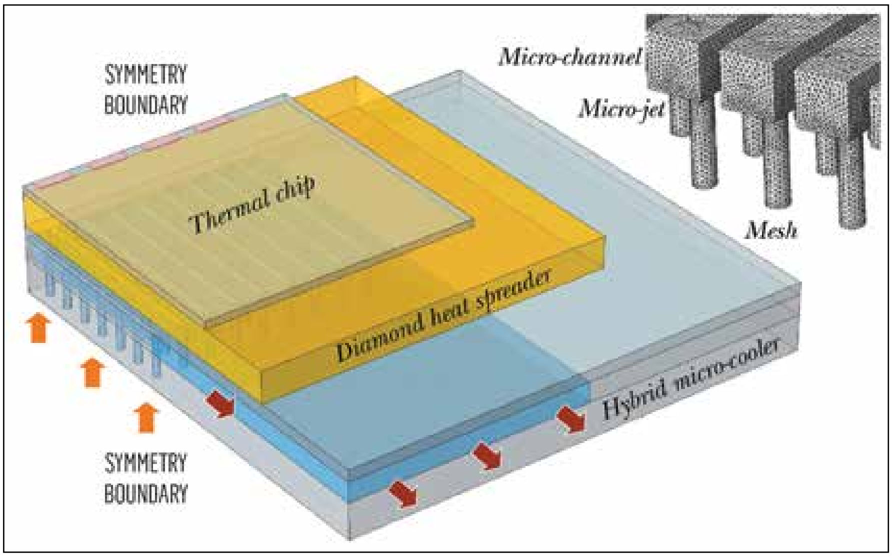

Figure 2: Quarter geometry numerical model (with the micro-channel cooler in blue).

4. NUMERICAL MODEL

Numerical thermal simulations for the test configuration were performed using commercially available finite element software [5]. Taking advantage of the symmetries in the system, only a quarter of the structure was modelled with symmetrical boundary conditions applied, as is illustrated in Figure 2. Silicon thermal conductivity was modelled as temperature dependent using the relationship:

$$k_{si} = 152\times(298/T)^{1.334} \qquad (1)$$

where T is temperature (K) and k_{si} is thermal conductivity (W/m-K).

The thermal conductivity of the applied solder material, Eutectic Gold/Tin (Au/Sn), is assumed to be constant at 57 W/m-K [6]. The Au/Sn bonding layer of 5µm thickness is assumed between silicon and diamond contact interfaces. Chip heat fluxes are prescribed on the hotspot heaters only.

5. RESULTS

A comparison of measured and predicted maximum chip temperature is shown in Figure 3 for structures with and without a diamond heat spreader. Overall, it is observed that experimental measurements and numerical predictions are in close agreement.

Without the diamond heat spreader, the structure can dissipate 30W heating power (hotspot heat flux 2.8 kW/cm²) and 70W (6.5 kW/cm²), while maintaining the maximum hotspot temperature (as measured at the die surface) under 80°C and 180°C, respectively. With the diamond heat spreader, the heat dissipation is improved significantly to 5 kW/cm² (for 54W) and 6.5 kW/cm² (at 70W heating power). Maximum hotspot temperature is reduced by approximately 26% in both cases. To maintain the chip temperature under 180˚C, the structure having the diamond heat spreader can dissipate around 100W heating power (hotspot heat flux 9.2 kW/cm²). Without diamond, power dissipation is reduced to 70W.

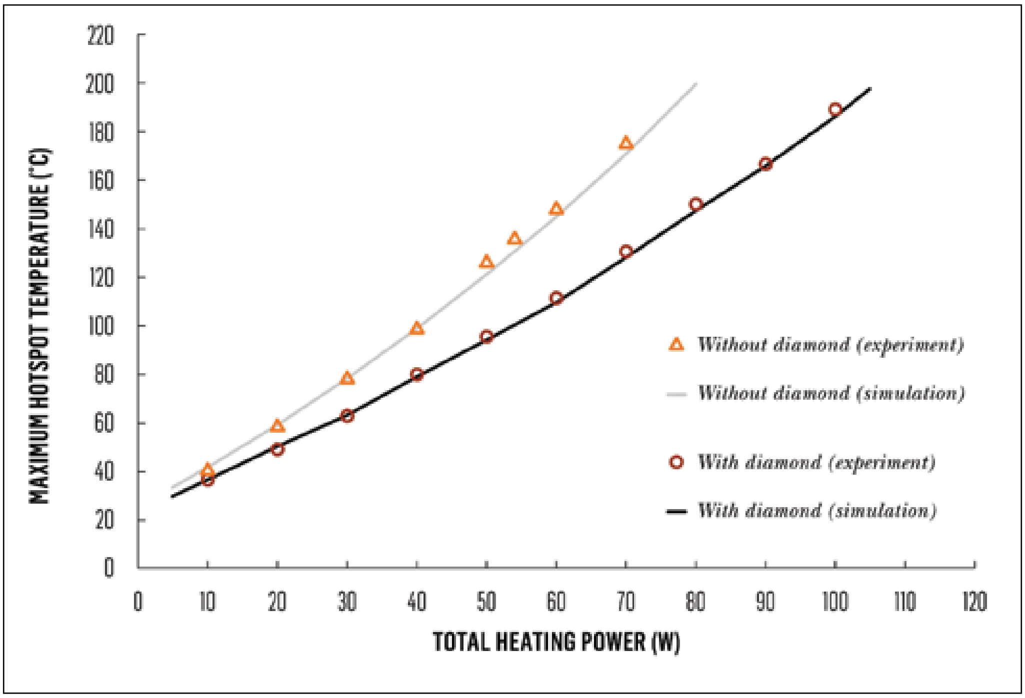

Figure 3: Comparison of measured and predicted maximum chip hotspot temperature for different heating powers with and without a diamond heat spreader.

For chip power dissipation of 54W (5 kW/cm^2), the measured temperature distribution on the top chip surface is shown in Figure 4, for cases using and not using a CVD diamond heat spreader. The maximum temperature of the measured hotspot located near the chip edge is 8°C lower than in the center of the structure without diamond heat spreader. Including the diamond heat spreader results in a 2°C peak temperature differences between the hotspots located near the chip edge and center.

The experiment was repeated using a diamond heat spreader having a lower thermal conductivity of 1500 W/m-K rather than 2000 W/m-K. As observed in Figure 5, for the same power dissipation, the change in the maximum hotspot temperature rise using diamond having a thermal conductivity of 1500 W/m-K is within 2% of that for 2000 W/m-K.

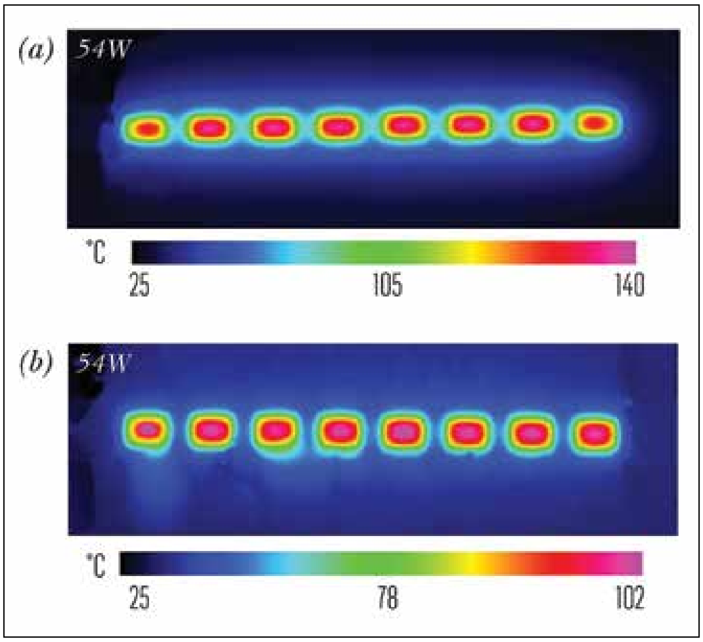

Figure 4: Measured infrared thermographs of the heating areas on the thermal test chip (a) without and (b) with diamond heat spreader for 54W power dissipation. The maximum scale value reflects the peak temperature.

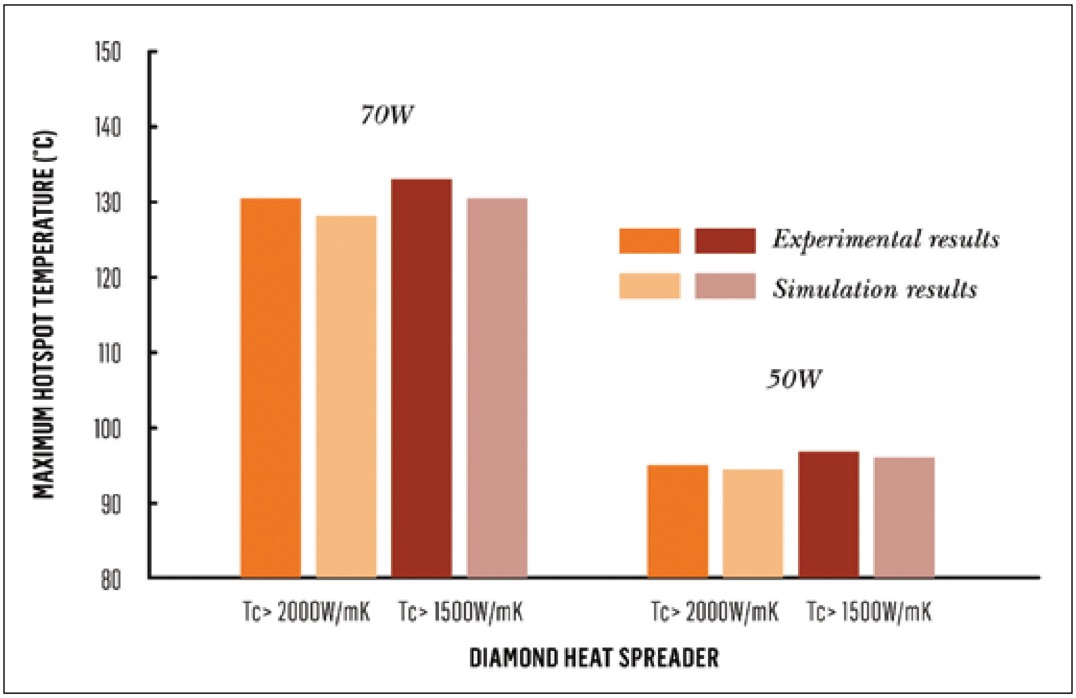

Figure 5: Comparison of measured and predicted diamond heat spreader thermal performance as function of thermal conductivity and chip power dissipation.

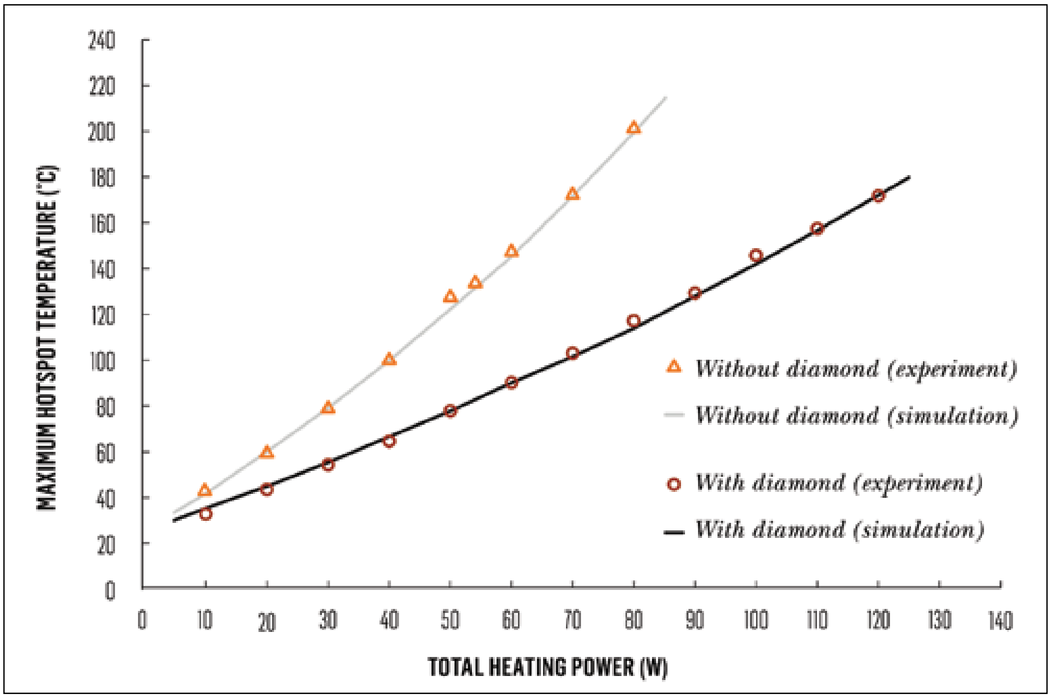

Figure 6: Maximum hotspot temperature as a function of heating power with and without the diamond heat spreader having a thermal conductivity of 2000 W/m-K.

Additional experimental tests and simulations were conducted on a thermal test chip of 100µm thickness. Figure 6 shows the comparison results of the thermal effect. Compared with the results in Figure 3, without the diamond heat spreader, 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, using a chip thickness of 100µm, with smaller thermal resistance between the heat source and the heat spreader, will improve heat dissipation. The diamond heat spreader can dissipate 110W of heating power (10.2 kW/cm^2) while maintaining the maximum hotspot temperature under 160°C. To dissipate 70W heating power, the diamond heat spreader can reduce by 40% the maximum hotspot temperature. It should also be noted that when using the CVD diamond, the heat flux distribution on the top surface of the silicon micro-cooler for the structure significantly changes. The maximum heat flux is reduced from 2.66kW/cm^2 to about 0.39kW/cm^2. 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 73% using the diamond heat spreader for the hotspot thermal management.

6. SPREADER THICKNESS INVESTIGATION

Additional simulations were performed to investigate the effect of the diamond heat spreader having a thermal conductivity of 2000 W/m-K and thickness ranging between 100µm and 700µm. Figure 7 illustrates the variations of the maximum hotspot temperature and the maximum heat flux at the top surface of the silicon micro-cooler.

Increasing heat spreader thickness will cause a reduction in temperature and heat flux. The thermal performance is only slightly improved by increasing the thickness from 400µm to 700µm, but is more pronounced in the thickness range between 100µm to 400µm, where the maximum hotspot temperature and the heat flux can be reduced by around 12% and 63%, respectively. Changing heat spreader thickness will also affect the temperature distribution. For 110W power heating, the peak temperature variation rates of the hotspots are 6.9%, 3.2% and 2.6% for heat spreader thicknesses of 100µm, 400µm and 700µm, respectively.

The component assembly (Figure 1) has two bonding layers, one between the chip and heat spreader and the other between micro-cooler and heat spreader. These layers are critical to assure low thermal resistance. In the experimental tests, the thickness of both bonding layers is approximately 5µm. Figure 8 shows the predicted temperature profile vertically from the silicon thermal chip to the micro-cooler. To dissipate 110W power, the temperature rise caused at the chip-diamond bonding layer is around 8.1°C, while at the diamond-cooler bonding layer the temperature rise is negligible. The bonding layer on the topside of the heat spreader, being much closer to the heat source, has a stronger effect on the hotspot cooling. Additional simulations show 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 from 5µm to 20µm, the temperature rise will increase by 12.9%. No significant temperature increase is predicted by doubling or quadrupling the thickness of the bonding layer at diamond-cooler interface.

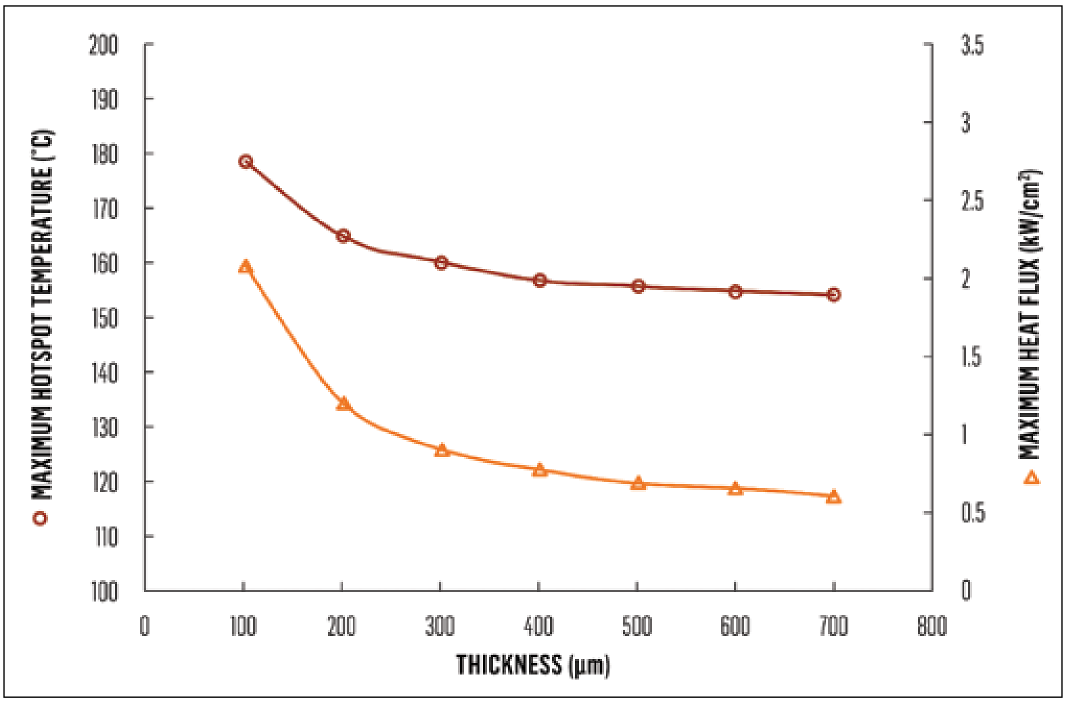

Figure 7: Predicted effect of diamond heat spreader thickness having a thermal conductivity of 2000 W/m-K on the thermal performance of the cooling structure having 110W power dissipation.

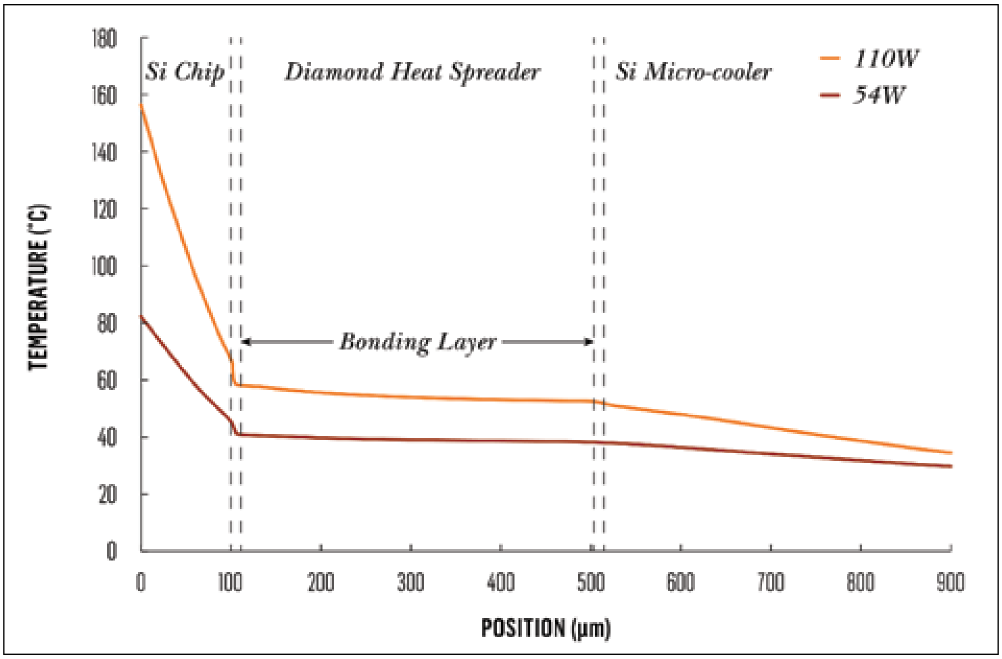

Figure 8: Predicted temperature profile across the micro-cooler structure having a diamond heat spreader.

7. CONCLUSION

This research investigated how using a CVD diamond heat spreader on a silicon-based hybrid micro-cooler will improve heat dissipation capability in a simulated GaN device. The simulations show using diamond heat spreaders significantly improves hotspot cooling capability. For the chip to dissipate 70W heat power, diamond heat spreaders with thermal conductivities of 2000 W/m-K and 1500 W/m-K can reduce the maximum hotspot temperature 40% and 38%, respectively. A 2000 W/m-K diamond heat spreader can dissipate 110W heating power (hotspot heat flux of 10.2kW/cm²) while maintaining the maximum hotspot temperature under 160°C. Also analyzed and compared were the thermal effects of the heat spreader thickness, diamond thermal conductivity and bonding layer. The thickness of the bonding layer at chip-diamond interface is critical for the thermal performance of the cooling solution. Overall, the results presented highlight that CVD diamond heat spreaders can be an effective thermal management strategy for high-power GaN devices.

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iNEMI Roadmap Identifies Trends Impacting Electronics Thermal Management

Azmat Malik
iNEMI

PREFACE

THE INTERNATIONAL ELECTRONICS MANUFACTURING INITIATIVE (iNEMI) is an industry-led consortium of approximately 100 leading electronics manufacturers, suppliers, associations, government agencies and universities. One of iNEMI's key initiatives is its biennial roadmap, which looks at the future technology requirements of the global electronics industry. It provides a 10-year outlook for electronics manufacturing, anticipating technology needs and identifying gaps.

The iNEMI roadmap is unique in scope. It covers the full electronics manufacturing supply chain and is an important tool for focusing research & development (R&D) priorities. This article discusses highlights from the Thermal Management Chapter of the 2015 Roadmap [1].

1. INTRODUCTION

The Thermal Management Chapter of the 2015 iNEMI Roadmap describes future thermal management technology needs across a broad range of product sectors, including: high-end systems, consumer/office systems, portable and wireless products, medical devices and systems, and light emitting diodes (LEDs). It assesses the current state of the art for all areas and then identifies the technology gaps that the industry will need to address to create tomorrow's products in these sectors.

The Thermal Management Roadmap also addresses the need to develop improved cooling technologies in terms of heat transfer processes, materials and innovative designs. If successfully implemented, enhanced thermal management will contribute to continued performance improvement trends and increased competitiveness of packaged electronic products. The roadmap identifies needs for further advances and developments in the following thermal technologies:

- thermal materials and thermal spreaders
- refrigeration cooling
- heat pipes
- liquid cooling
- thermal interfaces
- air cooling
- direct immersion cooling
- thermoelectric cooling, and
- thermal design modeling tools.

Here are highlights of some of these technologies, along with key challenges and R&D recommendations.

1.1 OVERVIEW/SITUATION ANALYSIS

Demand for more effective and cost-efficient means of removing heat from electronic systems continues to grow across all segments of the industry—from compact, portable electronics to large, high-end systems. It is a particular concern for power electronics associated with transportation and the electrical grid. In the absence of major new breakthroughs in thermal management technology, this demand is being met by broader, more aggressive use of, and incremental improvements in existing techniques, along with increased emphasis on reducing the generation of heat through improved product design.

Aluminum and copper heat sinks, with forced or natural air circulation, continue to dominate in terms of

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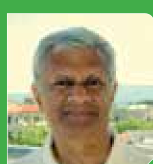

unit volume in the high-volume personal computers and consumer electronics applications. The growing trend toward higher performance electronics in smaller packages is forcing designers and manufacturers to consider phase change and liquid cooling techniques, albeit at higher cost. These have not yet made it to high volume because of limited data about cost, reliability, and longer-term efficacy.

Increasingly, there is recognition that reducing system power (power in, heat out) will not only reduce the demands on thermal management technologies, hence their cost, but will also result in direct and indirect energy savings at system and facility/plant levels. This reduced energy consumption will eventually result in operating cost reduction—and is leading to improved design practices that focus more closely on reducing the sources of heat in electronic devices. One example of this is non-uniform heat generation on devices, which causes localized "hot-spots" and requires thermal management based on a worst-case scenario. In high-volume and critical applications, where cost is no object, custom designs of cold plates can effectively manage hot-spots locally, without need for the entire thermal solution being scaled for the worst-case hot-spot scenario.

Expanded adoption of multi-core central processing units (CPUs) continue to help lower the thermal impact of high-performance devices in computing applications and are helping to mitigate, though not eliminate, the need for even more costly and aggressive cooling solutions. Also, increasing acceptance of electric and hybrid vehicles, renewable energy solutions and evolution of the smart grid is placing growing emphasis on thermal management techniques suited to the unique requirements of power electronics. Most high-performance applications have specific thermal solution expectations and must be dealt with based on specific design requirements. High-volume customer solutions, where cost is a key concern, are still driving the technology toward simpler and lower-cost "elegant" solutions.

Cost and time-to-market continue to play a critical role in maintaining competitiveness for all product sectors. To keep pace with the shrinking design-cycle time and to reduce development costs, the industry will rely on advances in computer-aided thermal design tools. Developments in thermal modeling tools to integrate electrical, thermal, fluid flow, and mechanical analysis and simulation in one user-friendly package continue to lag industry needs. The chapter identifies these tools as a major development need going forward. While many start-ups are addressing this gap, there have not been breakthroughs.

Thermal management has been a key enabling technology in the development of advanced micro-electronic packages and systems, and has facilitated many of the so-called *Moore's Law* advances in computers and electronic products. Thermal management entails a balanced combination of materials and techniques to optimize performance-cost designs. Increased complexity, density, and higher clock frequencies continue to push the thermal fluxes at chip level. These thermal demands propagate through the consumption chain (sub-system, system and facility).

The tradeoff between peak and average power is an important concern: high peak power will often mean a more expensive thermal management solution, while high average power will result in higher energy cost over the life of the system. There is reconsideration of the die junction temperature and there is a tendency to lower the acceptable temperature from previous norms. This will improve reliability and device life, while putting even greater demands on the thermal management system.

The state of the art of appropriate cooling solutions for electronics depends on the system power and the financial budget available for the cooling solution. There are thermal solutions to handle some of the most demanding needs, but the technology to do so does not always meet cost constraints.

Whenever possible, air-cooling is used, as it is the lowest cost. For cost-sensitive computing (desktop PC, a declining sector) this means air cooling of a heat sink, usually with fans to force air onto the heat sink to improve performance. Notebook computers often use a heat spreader with a heat pipe and a fan. However, weight and volume limitations constrain laptops' cooling performance, and that requires the use of lower power CPUs. Server computers use high-performance heat sinks and multiple fans to extend the limits of air cooling, and some medical equipment can afford liquid cooling. Acceptance of liquid cooling continues to increase as users get a better understanding of the costs and benefits associated with this solution.

The thermal management technology roadmap for typical power systems with different cooling schemes is shown in Figure 1. For 1U horizontal boxes with natural convection, systems now in the market are typically around 50W at ambient of 55°C at sea level.

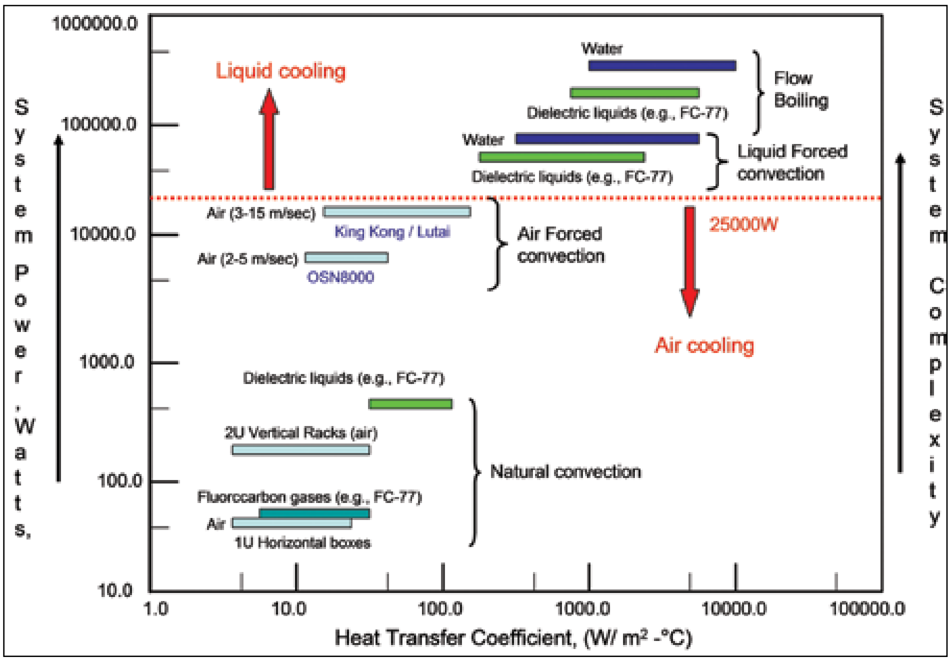

Figure 1: Thermal Management Technology Requirements and Choices [Source: Huawei Technologies].

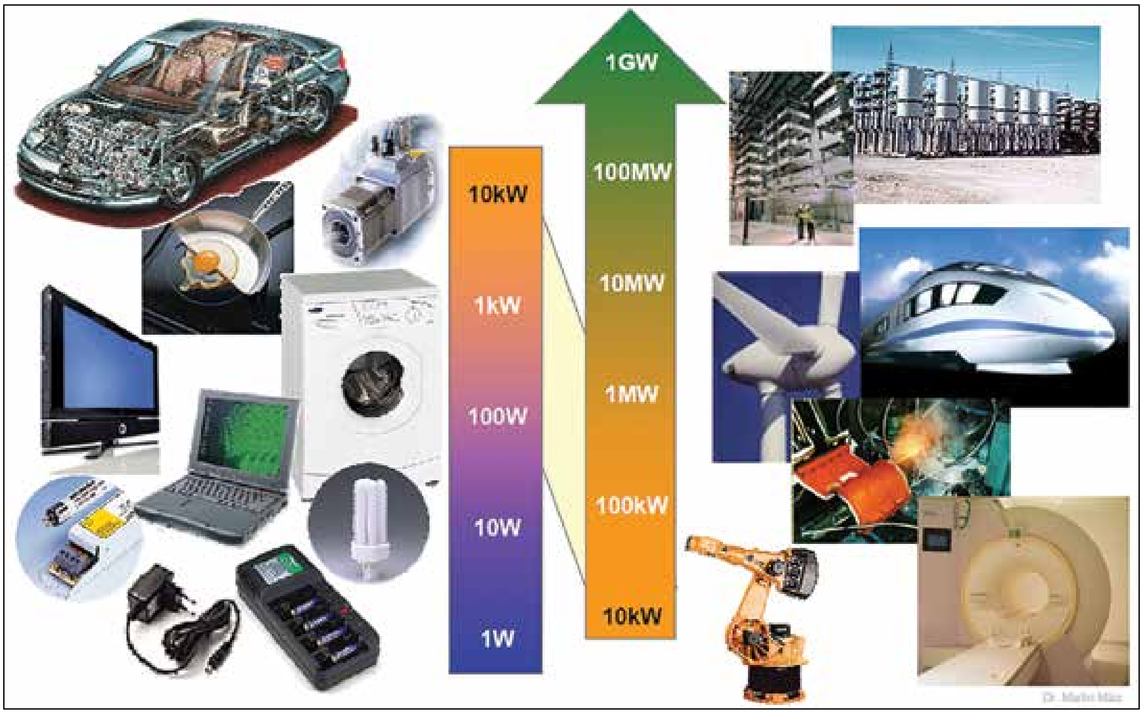

Figure 2: Range of power electronics applications [1].

Thermal management costs have historically been a small percentage of total system cost, ranging from less than 1% for some PCs to 3-5% for some large servers, and approaching 10% on the largest supercomputers. Failure to consider thermal issues while the design is still flexible limits the ability to make design tradeoffs that might significantly improve thermal management cost, reliability and performance. System and chip-level product designers are now engaging the thermal design team early in the design cycles to take advantage of the potential to improve the performance contribution and cost of the thermal solution.

Additionally, from a design perspective, a unified approach, looking at the entire system design rather than "stacking" margins and specs at sub-system levels, may be another way of achieving a more efficient thermal management solution.

2. THERMAL MANAGEMENT TECHNOLOGY CHALLENGES

2.1 POWER ELECTRONICS

Applications in power electronics have grown dramatically in the last few years because of greater need for electric power management and control (smart grid), renewable energy generation and control, and electric transportation—as well as a desire to improve operating efficiency of heavy systems, such as trains, industrial motors, and electric vehicles.

Power electronic converters are found wherever there is a need to modify the voltage, current or frequency. These range in power from few milliwatts (mW) in mobile phones to hundreds of megawatts (MW) in high-voltage direct current (HVDC) transmission systems. Usually, electronics are thought of in the framework of information technology, where speed is the primary interest. However, in the context of power electronics (Figure 2), there is a critical need for improved efficiency and reduced power losses.

There is a fundamental difference between planar microelectronics devices and power electronics devices. While microelectronics is essentially a surface-based technology (*i.e.*, the active area is on surface of the chip), in power electronics the current passes through the chip. This means that electrical contacts are on both sides and, because of the high voltages, insulation is necessary. For higher power, the chips are often stacked or connected in parallel in a multichip module. As 3-dimensional (3D) chip solutions get incorporated into volume production, the need for bulk thermal management will drive the development of cooling techniques such as liquid channels and graphene[1] layers.

Designers call on materials in power electronics systems to provide electrical and thermal conduction, insulation, protection, and mechanical stability, all with the objective of achieving the desired reliability. These properties usually cannot be considered in isolation. The coefficients of thermal expansion (CTEs) of the semiconductors and insulators are fixed. Metals can be matched by adding fillers such as aluminum-silicon-carbide (AlSiC), a mixture of aluminum, silicon and carbon/graphite, where silicon-carbide (SiC) has the low CTE to interface with silicon. Clearly, it is important to use materials with high

[1] Graphene has been shown to have unusually high thermal conductivity. Multiple layers of graphene show strong heat conducting properties that can be harnessed in removing dissipated heat from multilayer electronic devices. This has led to dramatic improvement in thermal characteristics, leading to lower temperatures even at higher processing speeds and higher power dissipation.

thermal conductivity and closely matched CTEs; applications using graphite must consider the fact that graphite is highly anisotropic with high thermal conductivity in the x-y plane only.

This metal-matrix composite (MMC) material is used in high-reliability traction applications because of the CTE match between the DCB/AMB (direct bond to copper-active metal braze) substrate to the AlSiC base plate, which protects the large area solder joint between them. Because of its lower weight, AlSiC may find use in aircraft applications.

2.2 LED THERMAL MANAGEMENT CHALLENGES

One particular challenge of light emitting diode (LED) thermal management is that, as with many semiconductor devices, the junction temperature of LED chips must be typically maintained well below 125°C — well below operating temperatures of traditional incandescent light sources.

The LED bulb is significantly more efficient in converting electricity to visible light, and the spectrum of that light is more effectively tailored to the photopic response of the human eye. As a result, the 60W equivalent LED bulb consumes only 13.5W of input power to deliver 2.5W of visible light power equivalent to 800 lm. This dramatic, 80 percent reduction in heat dissipation relative to the incandescent, 11W versus 55W, would seem to make thermal management of LED bulbs trivial. However, with a maximum allowable junction temperature of only 125°C, there is a much smaller temperature difference available to drive heat transfer from the source to the ambient. As a result, thermal management of the LED bulb is more challenging—requiring one-fourth to one-fifth the thermal resistance (°C/W). Making matters worse, natural convection and radiation heat transfer processes are significantly less effective at temperatures closer to ambient.

The vast majority of the waste heat in an LED system is generated in a very small volume within the millimeter-scale LED chip(s). While LED efficiency continues to improve, device manufacturers are packaging devices in increasingly smaller footprints, only exacerbating the heat density challenge.

2.3 DIRECT IMMERSION COOLING

It is possible that, in some cases, even with improved thermal interface materials, the internal temperature rise from the case-to-chip-junction may be too large because of the projected increase in power. In such instances it may be necessary to resort to direct immersion cooling with a dielectric liquid contacting the chip. Such cooling schemes could take the form of single-phase liquid-impingement jet cooling, pool boiling, or two-phase liquid spray cooling. Spray cooling of electronics within an enclosure has been implemented in military systems and in supercomputer modules. Whatever form the application of direct liquid immersion cooling may take, the major requirement will be that it is done at a reasonable cost, is reliable and occupies the minimum possible packaging volume.

2.4 REFRIGERATION COOLING

Both large servers and workstations have employed vapor compression cycle refrigeration to lower temperatures of the processor. Current technologies exhibit improvements of approximately two percent for every 10°C reduction in chip temperature. With this technology, the evaporator is mounted directly on the processor module. The remaining hardware (*i.e.*, compressor, condenser, valves, *etc.*) is typically packaged in a separate enclosure attached to the bottom of the system (workstation) or mounted inside the rack (servers). This technology has achieved chip temperatures in the range of -20 to 40°C. As with water cooling, the major requirement is to develop a refrigeration cooling technology that is low-cost, reliable, and occupies a minimum volume within the system.

2.5 THERMOELECTRIC COOLING

Thermoelectric coolers (TECs) offer the potential to enhance the cooling of electronic module packages to reduce chip junction temperatures or accommodate higher power. They also offer the advantages of being compact, quiet, and moving-parts-free—and they can provide an active control of temperature. TECs are limited in the magnitude of the heat flux that can be accommodated. TECs also exhibit a lower coefficient of performance (COP) than conventional refrigeration systems. The COP of a TEC will vary depending upon the usage conditions, but will typically be less than one. This means that the electrical power consumed by the TEC will be as great as, and often more than, the power dissipated by the component being cooled. These limitations are due to the currently available materials and methods of fabrication. As a result, thermoelectric devices have been restricted to applications characterized by relatively low heat flux.

Efforts are underway to improve the performance of TECs by the development of new thermoelectric materials and thin film coolers. If successful, these efforts promise increased heat pumping capability and higher COPs, which could open the door to a much broader application of thermoelectric devices to augment electronic cooling.

2.6 THERMAL MATERIALS

Heat removal, thermal stresses, warpage, weight, and cost are critical packaging issues. Traditional thermal management / packaging materials all have serious deficiencies. In general, traditional materials with high thermal conductivities have high CTEs, and materials with low CTEs have high densities and thermal conductivities that are similar or modestly better than that of aluminum. Chemical vapor deposition (CVD) diamond is a key exception.

In response to this problem, an increasing number of advanced materials have been investigated, and some are available for use. These materials offer: thermal conductivities up to more than four times that of copper, CTEs that can be tailored from –2 to +60 ppm/K, electrical resistivities ranging from very low to very high, extremely high strengths and stiffness, low densities, low cost and net-shape fabrication processes.

The payoffs are: improved performance or simplified thermal design, reduced power consumption, and reduced thermal stresses and warpage. Use of CTE matched materials allows direct solder attachment with hard solders (hard solders have better fatigue resistance than soft solders and fewer metallurgical problems), increased reliability, improved performance, weight savings up to 90%, size reductions up to 65%, reduced electromagnetic emissions, increased manufacturing yield and potential cost reductions. In addition, advanced materials make it possible to have low CTE, thermally conductive PCBs that can greatly increase the range of conductive cooling (in the aerospace industry, heat is removed entirely by use of PCB cold plates) and convective cooling.

A number of advanced materials are now being used in commercial and aerospace applications including: servers, plasma displays, notebook computers, printed circuit boards (PCBs), PCB cold plates, radio-frequency (RF) modules, power modules and optoelectronic packages. The rate of growth in the use of these materials has been dramatic. Components include carriers, heat spreaders, heat sinks, thermoelectric cooler substrates, LED packages and laser diode packages.

A significant need exists for new fluids that can be used for indirect liquid cooling (replacing water). That fluid would need to provide safer, more reliable operation in hostile environments, and also lower-cost direct (immersion) liquid cooling for the broad range of potential applications in commercial and military systems.

The critical issue of cost is complex and must be considered in the context of total cost over system life. Efficacy and appropriateness are prime factors, but beyond that, other issues needing to be evaluated include: reliability, life, mean time between failures (MTBF) and maintenance-repair-operating costs. Many factors also play a role in cost, such as complexity, size, flatness, surface finish requirements, and production run size.

Cost effectiveness depends on a particular application. For example, higher price and higher performance systems such as high-end servers and aerospace systems can tolerate higher thermal component costs than mobile phones. A key issue is the cost of competing approaches. For example, if the alternative is liquid cooling, an advanced material that is more expensive than a traditional one may be cost effective if it allows the use of convective air-cooling.

2.7 THERMAL DESIGN MODELING AND TOOLS

Sophisticated thermal design tools are now an essential element in the day-to-day design of electronic components, packages and systems. These tools take a variety of forms. Thermal conduction codes are used to model heat flow and temperatures within a package. Computational fluid dynamics (CFD) codes are used to model fluid flow around and through package assemblies—along with the associated pressure drop and heat transfer from exposed package surfaces to the fluid stream. In addition, some CFD and thermal conduction codes have conjugate capability, making it possible to model thermal conduction within the package structure simultaneously with modeling fluid flow and heat transfer in the cooling fluid.

Over the past decade, much has been done to improve the graphical user interface for problem definition and data input, especially with CFD codes tailored for use to model electronic equipment. Nonetheless, the industry needs further improvements to reduce the time consumed in defining the package geometry and structure and to enter related data preparatory to running a model. Seamless integration of computer-aided design (CAD) solid modeling tools, electronic design automation (EDA) tools, and CFD tools is needed to provide thermal designers the ability to take CAD solid-modeling-generated data and EDA-generated data and move them effortlessly into finite element thermal conduction modeling tools or CFD modeling tools.

Other needs requiring further effort:

- An improved ability to optimize thermal analysis codes for parallel processing to reduce solution time and provide the capability to model more complex thermal problems;
- A better way to enable CFD codes to better model turbulence and convective heat transfer in the transition flow regimes; and
- More extensive benchmarking to validate the accuracy of CFD codes.

3.0 SUMMARY OF TECHNOLOGY GAPS & SHOW-STOPPERS

The thermal technology improvements needed for each product sector to fill gaps and avoid show-stoppers are summarized in Table 1.

Table 1: Thermal improvements needed by product sector [1].

Product Sector	Requirements
Common Needs	• Improved thermal interfaces. • Improved thermal spreaders. • High-performance air cooling solutions. • Advanced modeling tools. • 3D designs cooling: ability to insert heat spreaders and phase change layers.
Portable/Wireless	• No significant improvements needed as long as battery power remains constrained.
High-End Systems	• Thermal integration with electromagnetic compatibility (EMC) shielding. • Low-cost, compact and reliable water cooling. • Low-cost, compact, reliable and efficient refrigeration. • High heat flux, efficient thermoelectric cooler. • Mechanically robust packages that minimize the thermal resistance path to air. • Low-cost, compact, and reliable dielectric liquid cooling. • Abatement of heat load impact on installation. • Outdoor structure (sheds) for remote stations: use materials that can passively reduce the need for active heating, ventilating, and air conditioning (HVAC)/fan load. • Quieter fans with efficient airflow design.
Automotive	• Low-cost, reliable heat pipe technology for automotive environment. • Passive electrical components/system level packaging materials capable of operating at 150°C. • Low-cost liquid or refrigerant cooling systems utilizing automotive cooling components. • Low-cost, self-contained, phase change materials to handle transient thermal events. • Analog and digital ICs capable of operating with T_J = 175°C. • Power transistor capable of operating with T_J = 200°C.
Medical	• Low-cost, compact and reliable water cooling. • High heat flux, efficient thermoelectric cooler. • Low-cost, compact, and reliable dielectric liquid cooling.
LEDs	• Development of LED packaging with low thermal resistance. • Low-cost, compact, and reliable dielectric liquid cooling. • SSI LED products have color shifts and lower lifetime performance — develop thermal management technologies to dissipate heat associated with high brightness light sources. • SSI-specific software and modeling tools to optimize assembly of LED and organic light-emitting diode (OLED) SSI devices are limited — develop SSI-specific software for designing and fabricating LED light engines and light sources within environmental and thermal constraints.
Power Electronics	• Geometries of electrolytic capacitors and magnetic components should be optimized to transfer and exchange heat better. • To best take advantage of the SiC junction field effect transistors (JFETs) (capability for higher voltages and higher operating temperatures in contrast to silicon devices) packages must be improved: materials, inductive wiring, creepage distances, *etc*. • Overall lower thermal resistance within power electronics system, especially in solders, glues, *etc*. — silver sintering as an attachment medium is in early stages of commercial use, and may offer other benefits. • Heat spreading: reliability of joining of heat pipes needs improvement; MMCs (such as aluminium/carbon) should be explored. • For optimization of heat exchange to ambient developments in two-phase cooling, pumpless liquid loops.

RECOMMENDATIONS

The following constitutes the major cooling technology areas identified for development and innovation by the Thermal Management Roadmap:

- Low-cost, higher-thermal conductivity packaging materials, such as adhesives, thermal pastes and thermal spreaders, for use in products ranging from high-performance computers to automotive applications.
- Advanced cooling technology, such as high-performance heat pipe / vapor chamber cooling technology, thermoelectric cooling technology, direct liquid cooling technology, as well as high-performance air-cooling and air-moving technologies.
- Closed loop, liquid-cooling solutions, which are compact, cost-effective and reliable.
- High-performance cooling systems that will minimize the impact on the environment within the customer's room and beyond.
- Advanced modeling tools that integrate the electrical, thermal, and mechanical aspects of package / product function, while providing enhanced usability and minimizing interface incompatibilities.
- Advanced 3D packaging techniques that can effectively remove heat from die not directly in contact with the PCB / substrate.
- Advanced experimental tools for flow, temperature and thermo-mechanical measurements for obtaining local and *in-situ* measurements in micro-cooling systems.

It is further recommended that industry participants should pool resources to fund cooling technology development, promote the involvement of university / research labs and establish a closer working relationship with vendors.

Finally, the industry needs to consider and evaluate changes in design processes to optimize system performance by (i) eliminating margin redundancies so costs may be minimized, and (ii) modified partitioning of component / system building blocks.

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2016 PRODUCTS & SERVICES INDEX

The Products & Services Index contains many categories to help find the products and services you need. Details of all the suppliers listed within each category can be found in the company directory, starting on page 33. To learn how to be included in this directory, e-mail editor@electronics-cooling.com.

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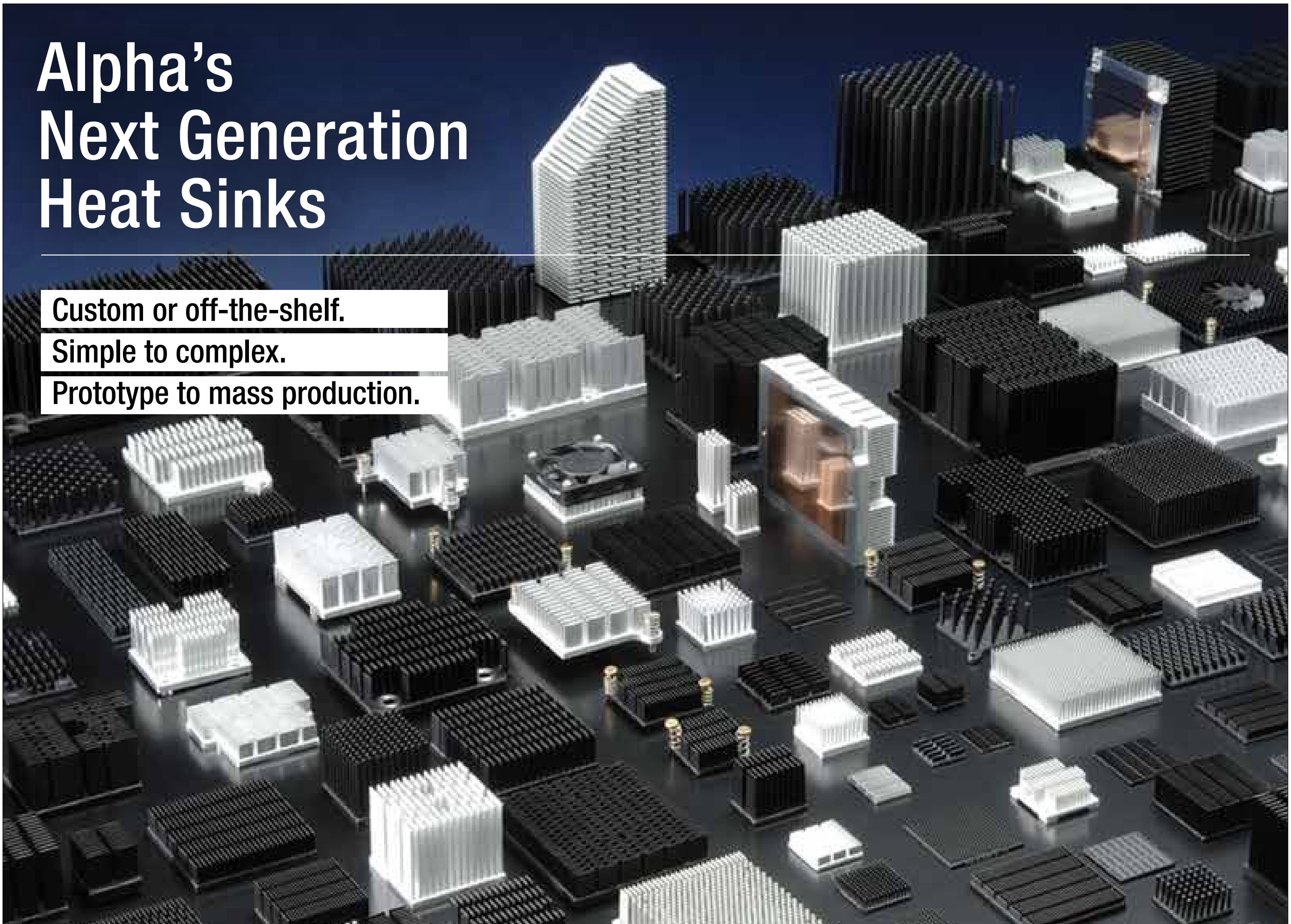

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