# A System to Package Perspective on Transient Thermal Management of Electronics

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*There are many applications throughout the military and commercial industries whose thermal profiles are dominated by intermittent and/or periodic pulsed thermal loads. Typical thermal solutions for transient applications focus on providing sufficient continuous cooling to address the peak thermal loads as if operating under steady-state conditions. Such a conservative approach guarantees satisfying the thermal challenge but can result in significant cooling overdesign, thus increasing the size, weight, and cost of the system. Confluent trends of increasing system complexity, component miniaturization, and increasing power density demands are further exacerbating the divergence of the optimal transient and steady-state solutions. Therefore, there needs to be a fundamental shift in the way thermal and packaging engineers approach design to focus on time domain heat transfer design and solutions. Due to the application-dependent nature of transient thermal solutions, it is essential to use a codesign approach such that the thermal and packaging engineers collaborate during the design phase with application and/or electronics engineers to ensure the solution meets the requirements. This paper will provide an overview of the types of transients to consider—from the transients that occur during switching at the chip surface all the way to the system-level transients which transfer heat to air. The paper will cover numerous ways of managing transient heat including phase change materials (PCMs), heat exchangers, advanced controls, and capacitance-based packaging. Moreover, synergies exist between approaches to include application of PCMs to increase thermal capacitance or active control mechanisms that are adapted and optimized for the time constants and needs of the specific application. It is the intent of this transient thermal management review to describe a wide range of areas in which transient thermal management for electronics is a factor of significance and to illustrate which specific implementations of transient thermal solutions are being explored for each area. The paper focuses on the needs and benefits of fundamentally shifting away from a steady-state thermal design mentality to one focused on transient thermal design through application-specific, codesigned approaches.* [DOI: 10.1115/1.4047474]

*Keywords: transient, thermal management, electronics packaging, phase change materials, codesign, thermal system*

## 1 Introduction

Transient thermal management is the application of principles of time-dependent heat transfer to avoid excessive temperature rise during pulsed or unsteady operating conditions. In contrast to steady-state designs, which focus on reducing thermal resistances in a system, transient thermal problems require considering both thermal resistances and the effective thermal capacitance of a system, which together dictate the time-dependent temperature rise.

The harsh reality for the thermal engineer is that "steady-state" is merely an illusion of design assumptions. Transient heat loads dominate in many applications, with the closest realization of steady-state only occurring in limited situations where the dominant thermal time constants are small relative to the timescale of changes to the boundary conditions of the system. As the magnitude, duration, and frequency of an increase in junction temperature can all have effects on component life [1], knowing the temperature history of a component is important.

Current trends in miniaturization and development of lightweight components and systems may have the side effect of reducing the effective thermal capacitance, which can exacerbate temperature ramps and place stringent demands on transient thermal management [2].

Electronics often do not reject heat directly to ambient but to a coolant loop system. Transient system-level considerations include the analysis of the time-domain response associated with the rejection of heat to ambient or to other coolant systems. Elements such as pumps and valve systems can introduce characteristic timescales associated with their operation, whereas elements with a large thermal capacitance, such as heat exchangers and cold plates, can serve to delay transient temperature rise.

Figure 1 illustrates the opportunities for both level 1 (system) and level 2 (package) transient thermal solutions that are discussed in this review. It cannot be understated that decisions regarding the selection of level 1 or 2 approaches are heavily dependent on the application. Determining the types of solutions will depend on the pulse magnitude and duration, the ability to alter and influence the packaging and heat exchangers, as well as other package and system limitations.

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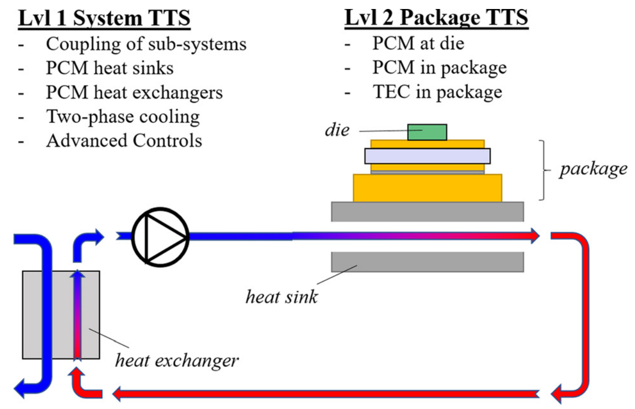


**Fig. 1 Transient thermal solutions at the system (level 1) and package (level 2) levels**

This review aims to bring a new perspective on the development and codesign of transient thermal management solutions at both the system and package levels for electronic components and introduce essential components for transient thermal management such as phase change materials (PCMs) and active control mechanisms. Transient thermal solutions and tools will be introduced for the system and package levels, respectively.

## 2 Transient Design

**2.1 Introduction to Thermal Transient Design.** Electronics are engineered to comply with the requirements from the electrical, mechanical, and thermal domains. Traditional design occurs iteratively, and a series of "best solutions" are developed in each domain independently. When devices are operated transiently at high power density, interactions between the domains increase and multidomain optimized, or codesigned, solutions are required. For example, an optimized low thermal resistance heat sink can have excellent steady-state performance but poor transient performance due to reduced thermal capacitance [2].

Codesign has the potential to significantly advance the state-of-the-art electronic packaging by moving away from a sequential design approach and replacing it with an inclusive design approach for which the electrical, thermal, and mechanical domains are all simultaneously considered [3]. Codesign requires a fundamental change in how thermal engineers, system engineers, and electrical engineers interface with each other, and it is necessary to create the right knowledge base, materials, tools, and communication across disciplines to allow for significant system improvements. Codesign at all levels and across the thermal–mechanical–electrical domain is essential for optimized performance. Transient solutions developed through codesign are therefore highly customized for the timescales of the specific application, and not as generally transferable to other applications as steady-state "best solutions."

Traditionally, thermal engineers use a thermal resistance network to evaluate the temperature rise between ambient and the junction temperature of a critical component in the electronics package. In order to design for transient performance, the thermal capacitance of each component needs to be added to the thermal resistance network. Dimensionless numbers such as the Biot and Fourier numbers play an important role in thermal transient modeling as they, respectively, describe the convective versus conductive and conductive versus energy storage heat transfer rates. These parameters assist in the determination of whether an element can be modeled as a single lumped thermal capacitance or as a set of discrete elements.

**2.2 Phase Change Materials.** Latent heat energy storage, primarily realized through a reversible endothermic phase transformation, offers a potential pathway to increase thermal capacitance with an order of magnitude or greater energy density than sensible heat storage. While boiling heat transfer and evaporators have extremely high effective heat transfer coefficients and latent heat energy storage, the need for condensers and pumping systems add significant complexity, size, weight, and system requirements [4]. PCMs, which rely on a solid–liquid or a solid–solid phase transition, offer a low-overhead passive approach to integrating latent heat capacity directly into an electronic package [5–7]. The relatively high enthalpy of melting has elevated interest in PCMs for passive thermal absorption during transient heat loads.

Ultimately, the ability of a PCM to buffer a thermal transient is limited by the rate at which heat can be absorbed into the PCM. This observation drove the development of a few closely related cooling power figures of merit, $\eta_q$, which are derived from analytical solutions of phase change problems under different boundary conditions (e.g., melting of a semi-infinite volume with a constant temperature surface boundary condition) [8–10]. This term identifies the material dependencies for cooling power capability given a particular geometry and boundary condition. For both constant temperature and constant heat flux boundary conditions into a semi-infinite volume, $\eta_q$ depends on the thermal conductivity of the liquid PCM, $k_l$, and on the volumetric latent heat of fusion, $L_v$, as $\eta_q \sim k_l L_v$. Thus, $\eta_q$ can indicate relative performance of different PCMs, or it can be used as a design objective to guide PCM materials design.

This realization allows for a strategy to evaluate the relative energy and power density of different candidate PCMs and to evaluate energy–power tradeoffs due to introducing conductive phases into a PCM layer (Fig. 2). As an example, by combining a phase with a large $k$ (e.g., copper) and a phase with a large $L_v$ (e.g., paraffin), cooling power density can be increased but at some cost to the effective energy storage density of the system (Fig. 2). Further development of PCMs capable of buffering temperature under high heat fluxes essentially falls into three

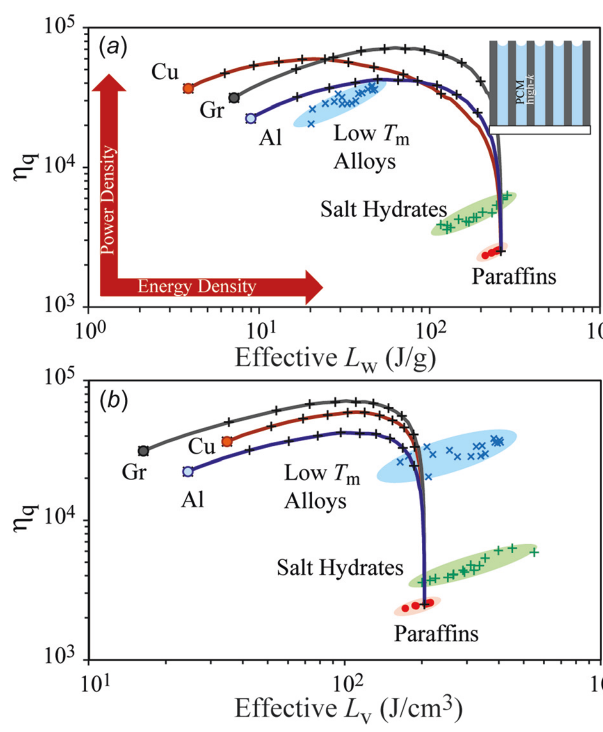


**Fig. 2 Energy density on (*a*) mass ($L_w$) and (*b*) volume ($L_v$) basis and cooling power figure of merit, $\eta_q$. Curves represent paraffin—high-*k* composites with different volume fraction of PCM in a lamellar configuration (see inset). $\eta_q = 1.29\sqrt{k_l L_v}/\sqrt{\Delta T}$, calculated for a wall superheat temperature of 10 °C [14].**

categories: (1) Development of metallic PCMs, which have a high intrinsic thermal conductivity due to their electrical conductivity. As an example, incorporation of high-$\eta_q$ alloy PCMs into an electronics package reduced the peak temperature $\sim$10 °C relative to the baseline package for <1 s heat pulses with a heat flux of $q'' = 11\,\mathrm{W/cm^2}$, whereas including low-$\eta_q$ paraffin PCMs increased the peak temperature by >20 °C [10]. (2) Developing composite energy storage materials based on a thermally conductive phase (typically a metal or graphite) and a thermally capacitive PCM phase in close proximity. As a recent example, high-$\eta_q$ alloy PCMs have been combined with conductive metallic foams to absorb heat pulses at a rate an order of magnitude higher than pure paraffin PCMs [11]. (3) Using micro- or nano-scale additives (particles, flakes, and wires) to improve conductivity. A former review by Kant et al. provided an overview of recent approaches including the use of macroscale metallic structures and metallic meshes, particle additives, and encapsulation techniques [12].

A relatively rich set of melting temperatures and enthalpies are known for metallic PCMs, due to their common use as solder alloys [13]. These materials are favorable due to their high intrinsic thermal conductivity but suffer from high density and air sensitivity.

Composite PCMs are of great interest because they allow exquisite spatial control of thermal properties simply by spatially varying the volume fraction and orientation of the different phases in the system. This introduces an opportunity to apply materials-by-design principles to attain optimal structures for some desired performance metric (e.g., rate of heat absorption per unit mass) [14,15]. As examples, incorporation of metal foams [16,17] or meshes [18] offer the advantage of providing a higher conductivity pathway for heat conduction into a surrounding PCM matrix, and the use of expanded graphite foams can even do so with minimal weight addition [19]. Following this design approach, compressed expanded natural graphite embedded with paraffin wax can increase the rate of heat absorption by nearly an order of magnitude over pure paraffins, while maintaining over 70% of the energy density of the pure paraffin material [14]. Others have achieved further improvements in thermal performance using embedded heat-pipes with fin structures [20,21].

In addition to embedded conductive structures, a number of efforts have investigated the incorporation of nano-additives for enhancing thermal properties, of which some notable instances are summarized in Table 1. Metallic nanoparticle additives promise improved thermal conductivity of organic PCMs. Some examples include Au nanoparticles in sorbitol [22], Ag nanowires in 1-tetradecanol [22,23], and even Cu in water/ice [23,24]. In the case of the Ag nanowires, a high particle loading accomplished significant conductivity improvements, but at the cost of a large volume fraction. Contrarily, a surprising increase in conductivity was seen in the Au-sorbitol composite with very low loading, which was attributed to induced crystalline phases [22]. This can explain observations when using nonmetallic additives, such as $TiO_2$ in palmitic acid, which show significant conductivity improvements in addition to increased latent heat and crystalline stability [22,25]. Likewise, iron oxide nanoparticles in paraffin [25–27] and organic esters having Ag-$TiO_2$ [26–28] were seen to have similar improvements.

A number of paraffin investigations with carbon nanomaterials, including graphite nanofibers [28–30], carbon nanotubes [29–32], graphene [31–34], and graphene oxide [33–35], have shown improved thermal conductivities as well as augmented latent heat and melting temperatures. But even beyond paraffins, graphene-based PCM alterations have also been demonstrated in PCMs of similar chemistry such as lauric acid [35] and a blend of fatty acids in vegetable oils [35–37].

While many of these efforts have highlighted the conductivity gains, perhaps the most interesting effect is noticed in the augmentation of melting temperatures and latent heat (see Table 1). As compiled by Kant et al., the reports of paraffin composites with carbon nanomaterials showed mixed changes in latent heat depending on the size of nanotubes and nanofibers embedded [12]. Considering the reports of Liu et al. [22] and enthalpy increases in Ref. [23], nano-additives may induce a physicochemical interaction between the nanoparticle inclusions and surface ordering and crystallinity of the PCM. Moreover, Khodadadi and Hosseinizadeh [24] observed a more rapid energy release rate in their Cu–$H_2O$ nanocomposite/nanofluid, indicating a contribution to the phase change dynamics itself. While still not fully comprehended, the continued advancement in the understanding of these particle-PCM interaction dynamics will be critical in designing the next generation of passive heat removal technology.

## 3 System-Level Need for Transient Thermal Management

**3.1 Motivation.** Components generally do not work in isolation but are part of an overall system with multicomponent interactions. Due to the increase in electrification of many applications [38], electrical systems are becoming more prevalent and power dense, thus increasing the needs and complexity of the thermal

**Table 1 Thermal conductivity and latent heat changes for various PCM–nanoparticle composites**

| PCM host | Nanoparticle | Thermal conductivity change | Latent heat change | References |
|---|---|---|---|---|
| Paraffin | Magnetite (iron oxide) | +48% (10 wt % nano particles)<br>+60% (20 wt % nano particles) | +8% | [26] |
| | Magnetite | N/A | +20% | [27] |
| | (i) Multiwalled carbon nanotubes (MWCNTs)<br>(ii) Al<br>(iii) Titanium dioxide ($TiO_2$)<br>(iv) Graphene | (i) +1036%<br>(ii) +354%<br>(iii) +127%<br>(iv) +3170% | N/A | [33] |
| | Graphite nanofibers | +11,800% | N/A | [29] |
| | (i) MWCNT<br>(ii) Graphite | N/A | −3.6 to 12% (worst case) | [31] |
| | Graphene oxide | +222% | −48.3% (paraffin–48 wt %) | [35] |
| Expanded pearlite (60 wt %) *n*-Eicosane (C20) composite | Carbon nanotubes | +113.3% | +2.33% | [32] |
| Docsane | Graphene | +100% | + 2.62% | [34] |
| Sorbitol | Au | Up to +7% | +50 to 130% (depends on wt %) | [22] |
| Palmitic acid | $TiO_2$ | Up to +80% | Down to −15% | [25] |
| "Bio-based" fatty acids | (i) Carbon nanotubes<br>(ii) Graphite nanoplatelets | (i) +78%<br>(ii) +248% | (i) −9.1%<br>(ii) −0.7% | [37] |

system(s). For example, an electric or hybrid electric vehicle requires independent thermal management of the passenger compartment, engine system, and power conversion and battery systems. Tolbert et al. [39] demonstrated the complex transient loading associated with SiC power electronics employed in hybrid electric vehicles (traction drives) over a typical urban drive cycle.

**3.2 System-Level Transient Thermal Solutions.** Novel transient thermal solutions that are being investigated at the system level include thermally coupling subsystems, PCM–heat sinks, PCM–heat exchangers, two-phase cooling, and advanced controls.

Coupling of thermal loops is presented by Zhou [41], who illustrates how the engine cooling system, passenger heating, ventilation, and air conditioning, system electronics, battery thermal management system (Fig. 3), and electric drive system can all be independent cooling loops but thermally coupled. A single refrigeration loop provides cooling to both the passenger heating, ventilation, and air conditioning and battery thermal management system through a three fluid heat exchanger. In this example, heat from the electric motor assists in bringing the battery pack to temperature, and excess heat from one loop can be rejected to another cooling loop to manage temperatures during transient loads.

Heat sinks with embedded PCMs have also been studied in the context of improving thermal capacitance. A number of efforts have investigated optimal configurations to enhance conduction of heat into the PCM. Initially, researchers examined the use of conductive housings enabled on a quad flat pack package [42]. Other efforts focused on fin structures and embedded metallic foams to enhance conduction to the PCM [43–45] and the interplay of thermal rejection capability with PCM selection and fin presence [46]. Efforts have also been undertaken to identify the critical dimensions for optimal phase change performance in a PCM-integrated heat sink [47,48].

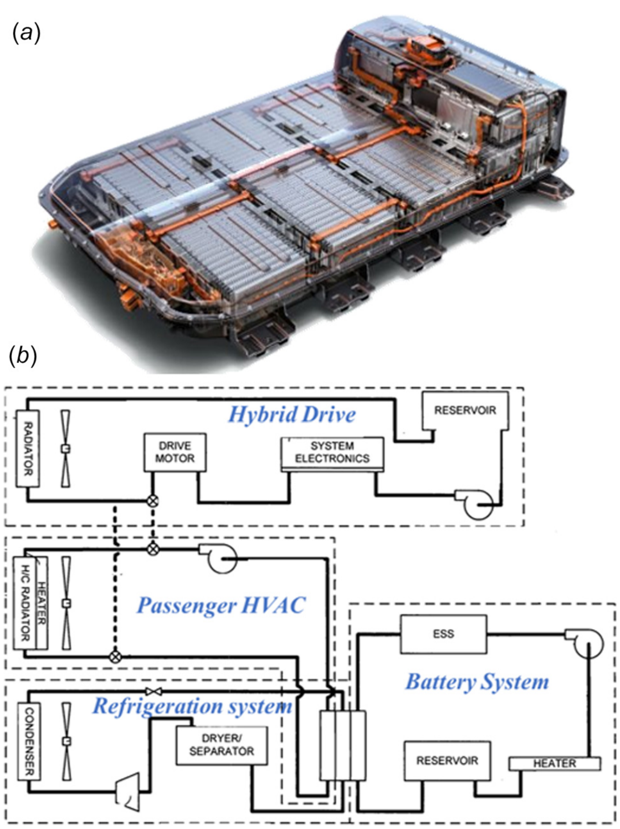


**Fig. 3 (*a*) Chevy bolt battery system, adapted from Ref. [40] and (*b*) thermally coupled cooling loops, adapted from Ref. [41]**

Topology optimization studies have been explored to develop high performance PCM heat sinks [49–51]. This includes attempts to balance latent heat rejection with conduction and convection in a two layer additive fin assembly (Fig. 4), where a lower tier conducts heat into both the PCM and an air-cooled second tier [52].

Heat exchangers form another, perhaps favorable, location for thermal capacitance enhancement through PCMs due to their inherent large surface area to volume ratio, reducing the potential conduction path length for the PCM layer [7]. New additive manufacturing methods have allowed for such new and innovative concepts to be developed.

Figure 5 illustrates an example of a new heat exchanger concept where a trifurcating heat exchanger design from Gerstler and Erno [54] is adapted for a third fluid cavity which can contain a PCM.

System-level transient modeling tools have also enabled advanced system integration approaches, such as model-based optimal control [55] and model predictive control (MPC) [56]. Of particular interest to the high-power electronics packaging community is the ability to predict and avoid dangerous operating conditions for components directly cooled by two-phase flow. Yang et al. [56] showed that a physics-based transient model of a vapor cycle system for high heat flux cold plate evaporators could capture nonlinear, dynamic behavior at the component level and its propagation to the system level. Subsequently, they were able to derive a feedforward MPC controller using their model that avoided dryout failure modes during sudden heat load changes. The results demonstrate a critical challenge arising from the disparity between device/package-level characteristic timescales and system-level characteristic timescales: driving toward low thermal mass at the device level causes rises in heat flux demand on the cooling loop at rates faster than it is capable of responding. MPC or model-tuned control schema provides a promising avenue for addressing this challenge.

**3.3 Tools and Methodology for System Thermal Transient Management.** The aforementioned examples illustrate a dynamic interplay between system components which underscores the importance of design coordination between engineering teams, traditionally been managed by "integration engineers." However, business demands or lack of definitive performance obstacles generally lead to serialization of design efforts. As next-generation electronics performance demands emerge, codesign tools offer a pathway toward enabling optimally coordinated systems across multiple design aspects.

This need for codesign becomes evident in Ref. [57] where Walters et al. illustrated the complex thermal, mechanical, and electrical interaction between the jet engine and the systems onboard a future jet fighter (Fig. 6).

New tools such as ATTMOsphere [58] and its predecessor ATTMO [59,60] have enabled exploration of complex, multidomain, system-level transients in advanced thermal and power management architectures such as that discussed by Walters et al. [57]. McCarthy et al. [58] demonstrate the utility of such tools and models in their study of a notional air vehicle environmental control system architecture consisting of a combined air cycle system and vapor cycle system for cooling time-variant electronics loads simultaneously subjected to changing sink conditions (Fig. 7).

McCarthy et al. [60] showed that variations in the external temperature could be exploited to passively charge the vehicle's thermal energy storage (in jet fuel stores). Similarly, the reverse is also true: lower altitudes occurring later during flight can cause fuel tank temperature rise, reducing the cooling capacity.

These dynamic thermal system models allow rapid parametric design studies accounting for the effects of changing boundary conditions on available thermal energy storage to arrive at component sizes that are lower in weight and volume while still meeting design constraints.

It is clear that transient system-level modeling tools have the potential to provide design insights into complex, integrated

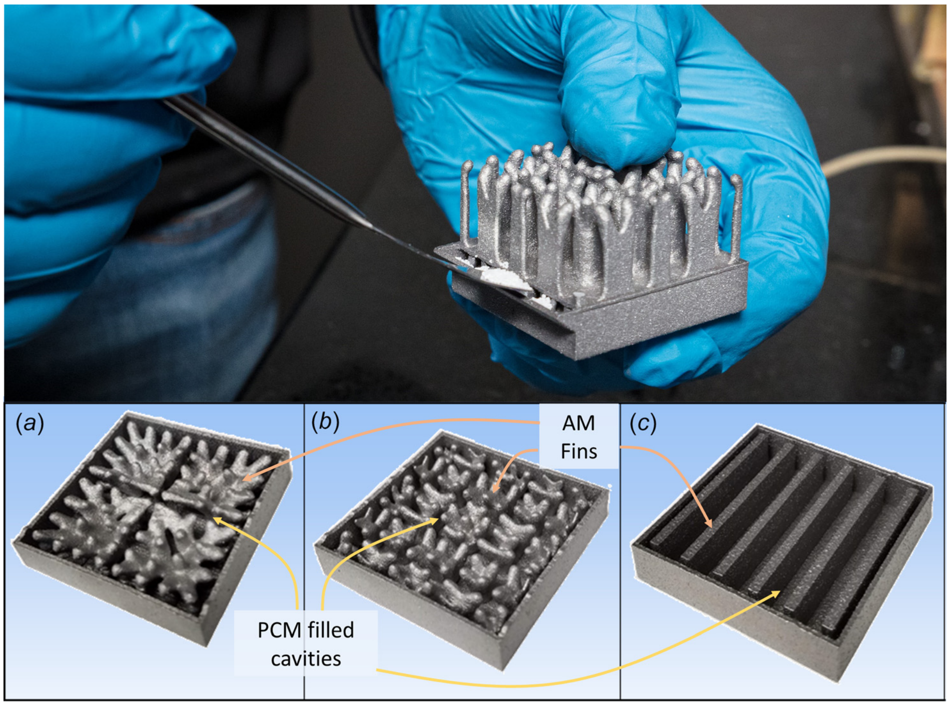


**Fig. 4 Two-tier PCM heat sink (top) utilizing topology optimization for combined latent heat, conduction and air cooled convection and (bottom) illustration of PCM fill geometry in lower tier**

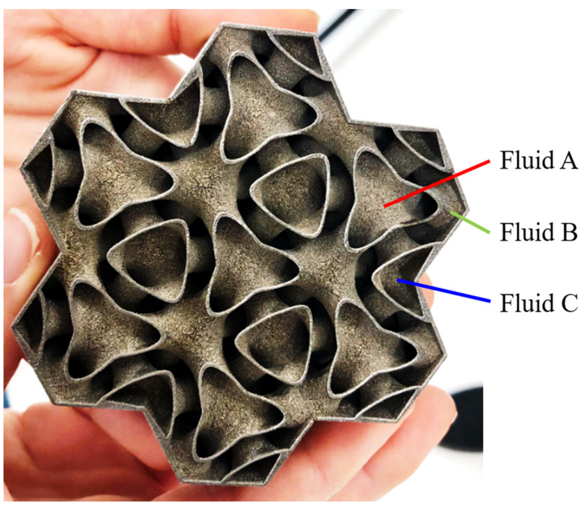


**Fig. 5 Nested three fluid trifurcating heat exchanger which can contain PCM in one of the three fluid cavities [53]**

thermal systems that are not easily captured by established design approaches.

## 4 Heat Generation—Transient Thermal Management of the Package

**4.1 Motivation.** With increasing growth in the electric vehicle/aircraft market, power electronics for drivetrains are subjected to highly variable loading profiles associated with usage (or "drive schedules") [61]. Correspondingly, the temperature variations experienced will precipitate any number of thermomechanical reliability challenges from wirebond fatigue to substrate mechanical failures [62,63].

Inside of an electronics package, the temperature of the device (logic chip, power semiconductor, etc.) often dictates the thermal solution. Maintaining the die temperature below its specified junction temperature limit ensures the expected device performance and reliable operation.

While steady-state power conversion applications have benefited from numerous packaging and cooling improvements, these solutions have been shown to have the potential for detrimental effects in transient applications as well as overdesigned cooling systems [2]. The primary goal of most package-level thermal management to date has been to increase power density within the electronic assembly by reducing thermal resistance. This has been accomplished mainly through (1) bringing cooling directly to the junction area to reduce the number of interfaces and/or (2) minimizing the conduction path with thinner, high conductivity materials. However, in doing so, the "thermal mass" ($m{\cdot}C$) of the system is consequently reduced, leading to potentially intensified temperature swings in response to variable power dissipation.

**4.2 Device Level Transients.** When considering the thermal response of the state-of-the-art wide-bandgap power electronic devices, it should be noted that power switches for electric motor inverters and AC-DC/DC-DC converters [64,65] do not operate in a continuous mode but instead dissipate heat under high-frequency pulsed-mode operation [66]. During this transient operation, the solution with the lowest steady-state thermal solution might still exhibit a large temperature excursion during short transient operation.

Figure 8(*a*) compares the channel temperature rise of a GaN HEMT and an $Al_{0.30}Ga_{0.70}N$ HEMT [67] under direct current (DC) and 10 kHz pulsed (10% duty cycle) conditions at diverse power dissipation levels. Measurements were performed using transient thermoreflectance imaging and nanoparticle-assisted Raman thermometry techniques [68]. As the operating conditions change from steady-state (DC) to pulsed, a dramatic reduction in temperature rise can be seen for the AlGaN HEMT. In stark contrast, the GaN HEMT does not seem affected.

The low thermal conductivity and thermal diffusivity of AlGaN ($k_{AlGaN} \sim 10$ W/m·K versus $k_{GaN} \sim 130$ W/m·K [69]) result in a longer thermal response time [70] than those of GaN counterparts. As shown in Fig. 8(*b*), the thermal time constant of the GaN

HEMT is an order of magnitude smaller than that of the AlGaN HEMT.

The trend shown in the experimental results of Fig. 8(*b*) can be compared and validated based on the inverse relationship between thermal diffusivity ($\alpha$) and thermal time constant ($\tau$) [71]

$$\tau \sim \frac{1}{\alpha} = \frac{\rho c_p}{k} \quad (1)$$

where $\rho$ is density, $c_p$ is the specific heat capacity at constant pressure, and $k$ is the thermal conductivity.

Utilizing the properties presented in Table 2, thermal diffusivities of $4.3 \times 10^{-5}$ $m^2 \cdot s^{-1}$ and $3.3 \times 10^{-6}$ $m^2 \cdot s^{-1}$ are obtained for GaN and $Al_{0.30}Ga_{0.70}N$, respectively, validating the approximate order of magnitude difference in thermal time constants.

However, it is important to note that while Fig. 8(*b*) demonstrates the impact longer thermal time constants can have on the device-level transient thermal response, it is ideally the thermal capacitance that should be increased for a transient cooling solution. The thermal time constant can also be defined as [71]

$$\tau = R_t C_t = R_t (\rho V c_p) \quad (2)$$

where $R_t$ is the thermal resistance, $C_t$ is the thermal capacitance, and $V$ is the volume. For the results in Fig. 8(*b*), the longer thermal time constant was a result of increased $R_t$ due to the low thermal conductivity in the AlGaN, as opposed to increased $C_t$.

Nonetheless, these results highlight that thermal management of pulse-powered components should not only aim for reducing the junction-to-package thermal resistance but also consider incorporating thermal capacitance into the cooling solution design to optimize the transient thermal response.

**4.3 Package Integrated Transient Thermal Solutions.** One of the primary places to explore the integration of transient thermal solutions is in the package near the junction. The proximity to the heat dissipating component allows a faster thermal time response which is important in many electronics systems [76–78]. However, the electronics application must be considered to develop the optimal design.

One approach to improve the system size and weight without sacrificing platform performance is by developing a package using PCMs chosen based on the application. For short pulses, metallic PCMs have a fast thermal response due to high thermal conductivity (high-$k$) but the weight, cost, and integration complexity limit their viability in applications. Alternatively, organic PCMs are inexpensive, lightweight, and can have very high latent heat of fusion, but they have very low thermal conductivity (low-$k$) compared to metals and thus cannot absorb heat quickly. The selection of the PCM for the application and appropriate integration into the package to ensure functionality are the primary considerations when incorporating PCMs in electronic assemblies.

To demonstrate the need to understand the application, Fig. 9 shows the thermal response of a chip bonded to a Cu substrate with various encapsulation materials—standard gel, pure copper, gallium (metallic PCM), and Pt29 (organic PCM) [6]. The standard gel encapsulant always results in the highest temperature while the paraffin wax PCM (Pt29) has a slightly lower temperature.

Between 13 and 110 s, the gallium outperforms the copper by up to 30 °C due to the latent heat absorption, and as an added benefit, it is over 30% lighter. But outside of those times, the copper results in lower temperatures due to its higher thermal conductivity. This understanding is important when considering transient design.

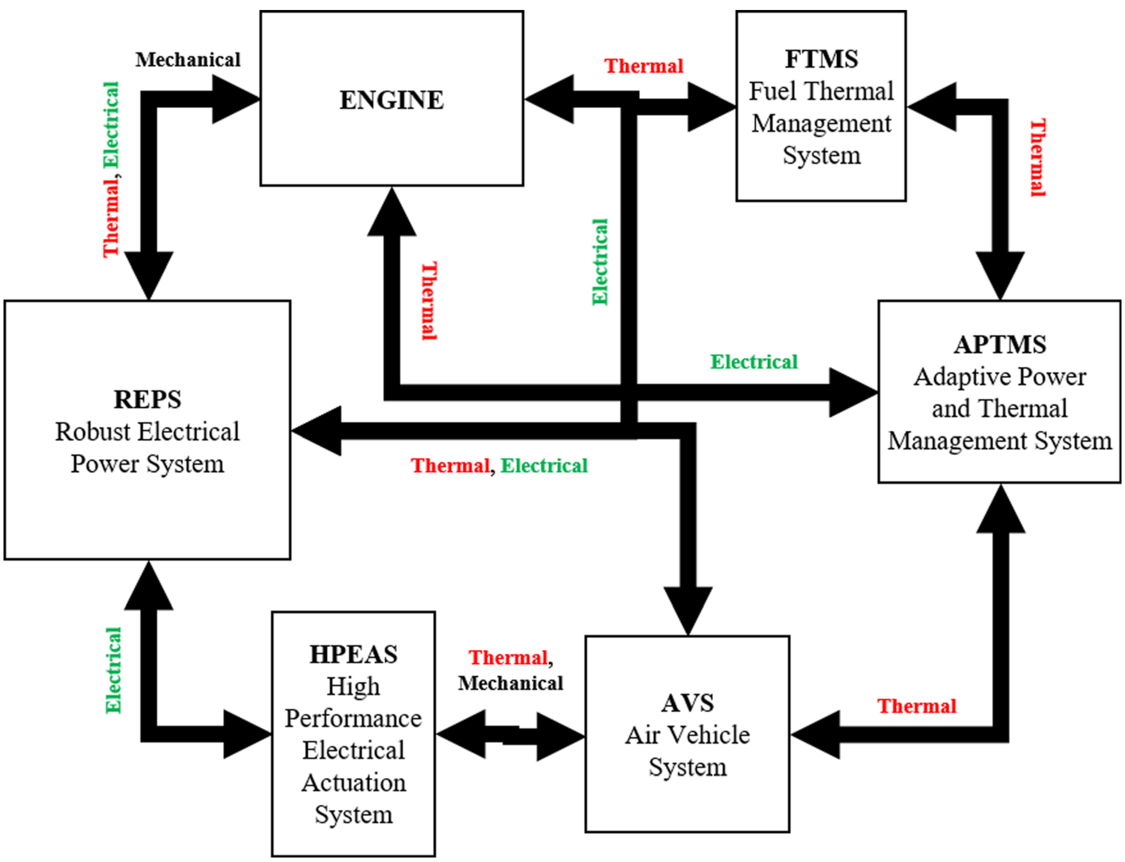


**Fig. 6 INVENT modeling scheme of thermal, mechanical, and electrical interactions between subsystems in a next generation jet fighter. Adapted from Ref. [57].**

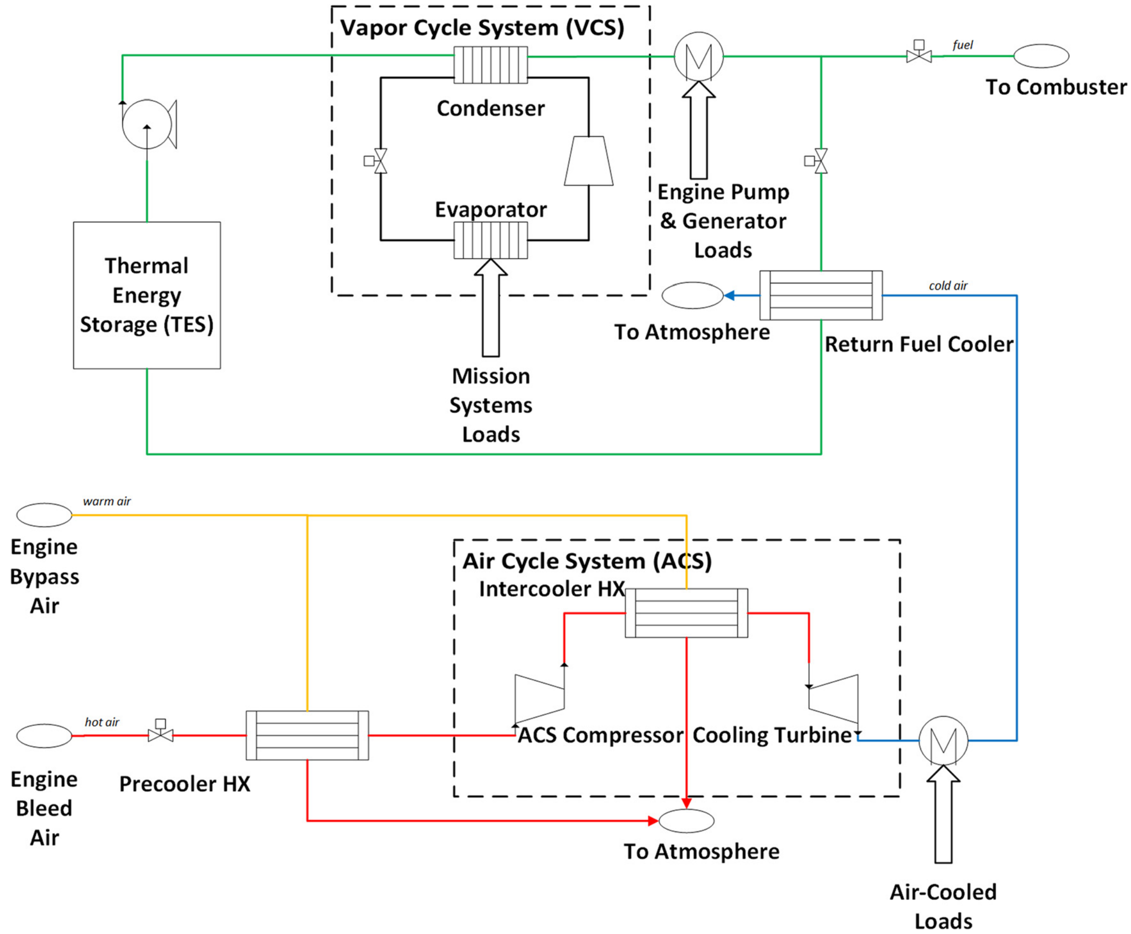


**Fig. 7 Simplified diagram of thermal management architecture modeled in Ref. [58]; solid lines indicate fluid paths**

The integration of metallic PCMs directly in contact with the top of a power device has shown the ability to significantly reduce the die temperature. As shown in Fig. 10 for a 20 ms pulse, the die temperature has been reduced almost 60 °C as compared to the standard dielectric gel [78].

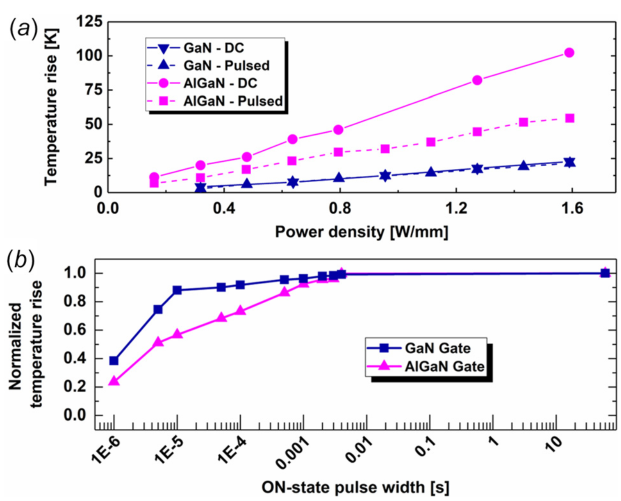


**Fig. 8 (*a*) The channel temperature rise of a GaN HEMT versus AlGaN HEMT under DC and 10 kHz pulsed operation. (*b*) Normalized temperature rise of the gate electrodes with respect to the steady-state temperature rise (24 °C and 68 °C for the GaN and AlGaN HEMTs, respectively) as a function of the ON-state pulse duration, with a power density of 1.6 W/mm.**

While still relatively new in literature, varying the location of PCMs in the package is gaining popularity. This includes technologies such as replacing the die attach with a metallic PCM, placing a PCM inside of the chip, and using a PCM as a thermal interface material. Any solution that focuses on the conductive path between the heat dissipating surface and the heat sink needs to be investigated for its effectiveness in the application. This is because the amount of PCM also plays a critical role in its ability to absorb the thermal transient. If a small amount of PCM is integrated, it will melt very quickly and the properties of the PCM in both the solid and liquid state are most likely worse than the material it would replace. Therefore, a sufficient amount of PCM is required for package integration to establish an effective thermal design.

Moving forward, timescale matching will play a critical role in PCM design and integration. The timescale matching PCMs incorporate metallic PCMs in conjunction with organic PCMs to leverage the benefits of each material. Timescale matching allows the high-*k* metallic PCMs to quickly absorb the initial pulse wave

**Table 2 Properties of GaN and $Al_{0.30}Ga_{0.70}N$ [72–75]**

| | GaN | $Al_{0.30}Ga_{0.70}N$ |
|---|---|---|
| $\rho$ (kg·m$^{-3}$) | 6150 | 5280 |
| $c_p$ (J·kg$^{-1}$·K$^{-1}$) | 490 | 570 |
| $k$ (W·m$^{-1}$·K$^{-1}$) | 130 | 10 |
| $\alpha$ (m$^2$·s$^{-1}$) | $4.3 \times 10^{-5}$ | $3.3 \times 10^{-6}$ |

Note: Linear interpolation was used to determine the density and specific heat capacity of $Al_{0.30}Ga_{0.70}N$.

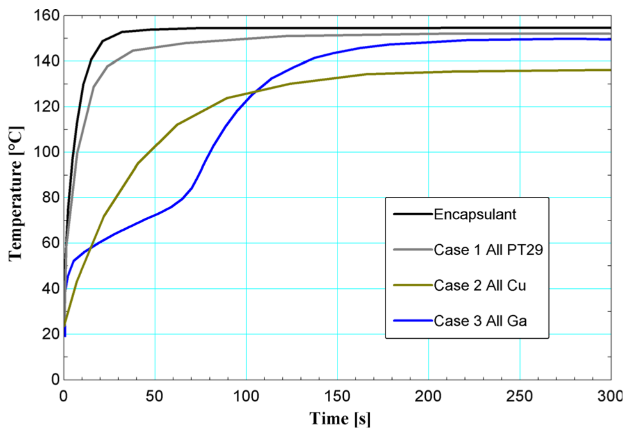


**Fig. 9 Maximum chip temperature versus time plot comparing a standard gel encapsulant to all PT29 (organic PCM), all copper, and all gallium (*m*-PCM) modeled in ParaPower [6]**

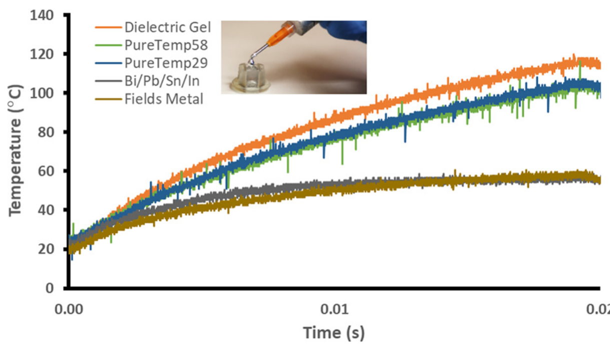


**Fig. 10 Evaluation of on die PCMs performance. Adapted from Ref. [78].**

(primary melt) while accommodating the slower heating of the low-*k* organic PCMs until they also melt (secondary melt) [5].

Another transient thermal management solution for package integration is the use of microthermoelectrics for active control. An example of this active in-package transient thermal management is presented by Bar-Cohen and Wang who pioneered embedded microthermoelectrics and demonstrated several degrees of cooling in hot-spot locations [79].

Green et al. [80] explored the use of in-package thermoelectrics combined with thermal energy storage in the form of PCMs (Fig. 11) to manage local hotspots. Thermoelectrics operate as microheat pumps and can be activated to mitigate transient thermal temperature rise by removing heat from the PCM.

Such technologies can be especially effective in enabling on-package silicon photonics as optical components require temperature stability and/or temperature control near the temperature sensitive components such that the laser diodes (LDs) and detectors do not experience any lasing wavelength shifts. However, thermoelectric-based approaches are not anticipated to be sufficient for the thermal management of wide-bandgap power electronics due to higher heat dissipation rates and the relatively low efficiency of thermoelectric coolers.

**4.4 Codesign Tools and Methodology.** There exists an increasing need for electronics package modeling tools which can quickly and accurately model the electrothermomechanical design space and incorporate novel materials such as PCMs. Army Research Laboratory (ARL) PARAPOWER [71,81,82], shown in Fig. 12, is an open-source design tool which can analyze parametric spaces, such as material types, material properties, layout designs,

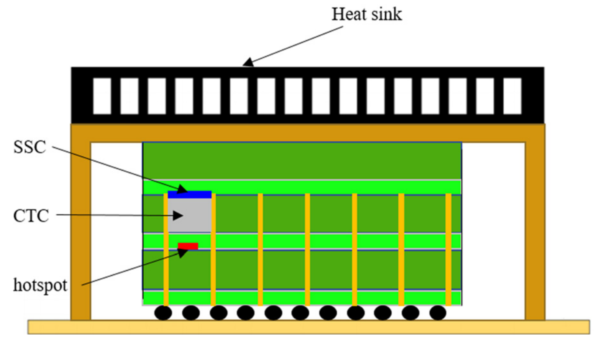


**Fig. 11 Schematic of an embedded in-package thermoelectric solid state cooler and PCM composite thermal capacitor thermal energy storage. Adapted from Ref. [80].**

geometries, heat sink selections, and heat sink placements, using time-varying heat inputs and solid–liquid PCMs.

ARL PARAPOWER is based on a thermal resistance network, which is a foundation of thermal analysis. The model is adaptable to any number of features, heat loads, and heat transfer conditions. In previous works [83,84], the authors demonstrated the implementation of a codesign approach using the PARAPOWER parametric analysis tool that evaluated both the thermal and coefficient of thermal expansion-mismatch stress aspects simultaneously. PARAPOWER has also been compared with finite element analysis (FEA) for model accuracy and speed in studies of traditional versus stacked high-V packages. In this study, for the same geometry, temperatures agreed within 3 °C and stresses agreed within 30%, but the run times for PARAPOWER were $\sim$100 $\times$ faster than FEA [85]. This speed and utility lends itself to more complicated transient thermal conditions, such as optimization of designs with embedded PCMs, wherein the codesign activities of sensitivity analysis, parametric analysis, and design optimization can be performed more expediently than more detailed and comprehensive FEA tools.

The power of design tools such as ARL PARAPOWER is most valuable in the ability to sweep design spaces to quickly find the optimal configuration for a given thermal pulse. As an example, PARAPOWER can be integrated with other computational design tools to optimize spatial distribution of different components, to analyze materials selection problems, or to optimize the distribution of different materials types to minimize the temperature rise at a critical junction under some prescribed thermal loads (Fig. 13). Moreover, when considering the temperature dependent properties of PCMs, such as melting temperature and phase-specific conductivity, tools like PARAPOWER provide the opportunity to leverage codesign in the selection and integration of capacitive thermal management in the context of transient power dissipation schemes. Such utility will be critical in delivering fully optimized electronics packaging for next generation electrified systems.

## 5 Conclusion

This work has sought to illustrate how the current trends in electronics are raising the importance of transient thermal management in designing robust and reliable systems. Specifically, component miniaturization, higher device power, and thermal cross-talk between multiple devices in a complex system require management of heat transfer and local temperature distribution in the time domain. This review has attempted to capture the state-of-the-art research activities in transient thermal management from the system level down to the component level. The ultimate goal of these activities is to deliver new transient thermal solutions and tools to practicing thermal engineers in order to design custom solutions for particular transient thermal problems.

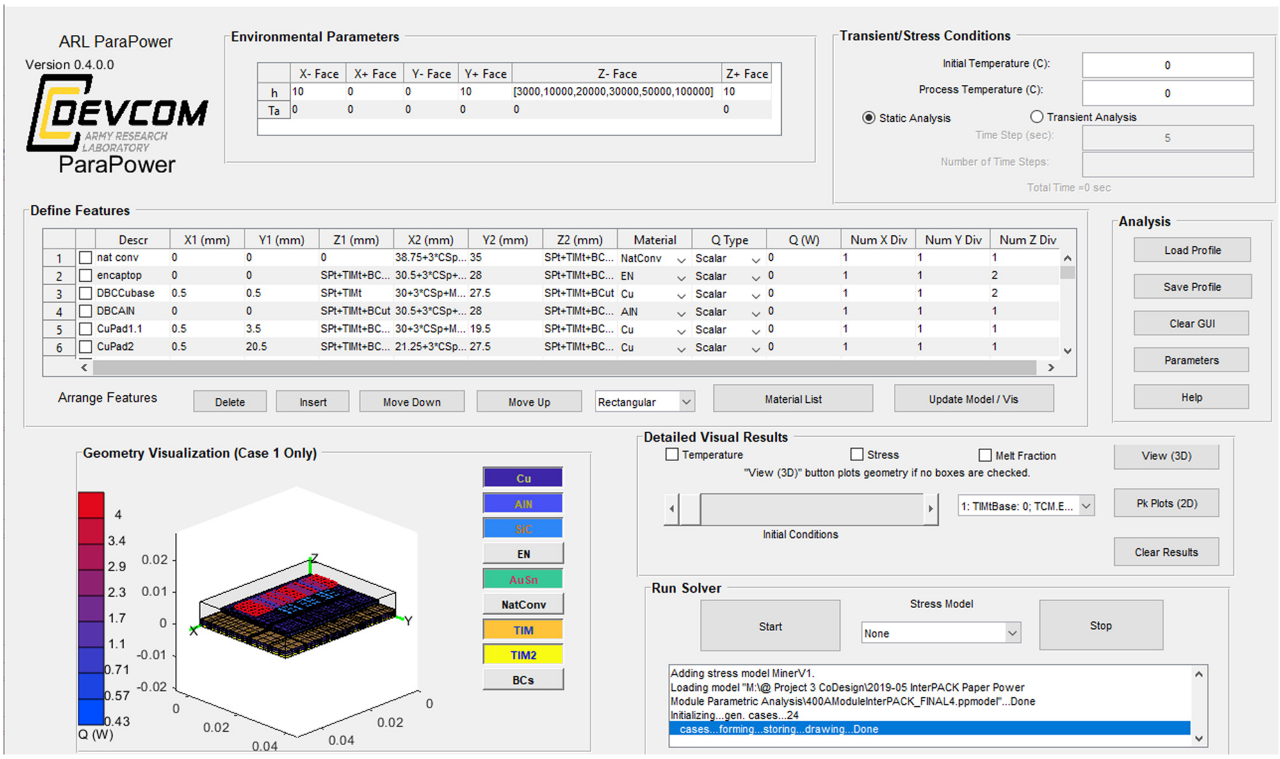


Fig. 12 ARL PARAPOWER software tool for electronics codesign[2]

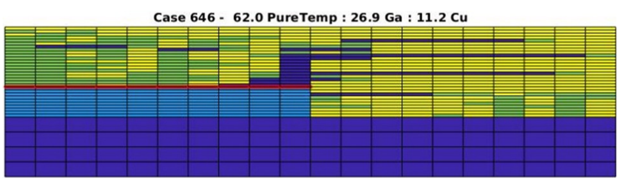


**Fig. 13 Cross section of SiC chip on substrate with a heated surface surrounded by a volume of encapsulant material composed of either a paraffin-based PCM, gallium, a low melting point alloy, or conductive copper. Distribution of encapsulant phases after a Monte Carlo-based genetic algorithm run for one million iterations to minimize temperature rise within the SiC die.**

At the system level, current activities are focused around effective integration of PCMs in heat sinks and heat exchangers, advanced controls, and system-level simulation tools which are composed of reduced-order compact models of the dynamic thermal response of individual components. Within power electronics packages, recent advances have focused on re-introducing thermal capacity into the package to buffer transient temperature rise through specifically engineered PCM volumes optimized for particular performance metrics. Similar efforts exist to integrate PCMs within heat exchangers to account for transients at the interfaces between electronic components and cooling loops. Finally, codesign techniques are necessary to harness the full capabilities of these individual elements, thereby resulting in optimal component-level designs. One recent advance in this area is ParaPower, a computational design tool, which specifically targets rapid parametric design and optimization of power electronics modules.

It is likely that the relative importance of transient thermal design will only increase in the near future. In response, it is of paramount importance to continue to advance the technologies and toolsets available to thermal engineers and to facilitate integrated thermal design bridging the relevant scales in both the time and physical domains.

[2]https://github.com/USArmyResearchLab/ParaPower/wiki

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## Nomenclature

$c_p$ = specific heat capacity ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
$C_t$ = thermal capacitance ($J{\cdot}K^{-1}$)
$K$ = thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
$k_l$ = thermal conductivity of the liquid ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
$L_v$ = volumetric enthalpy of fusion ($J{\cdot}m^{-3}$)
$L_w$ = specific enthalpy of fusion ($J{\cdot}kg^{-1}$)
$mC$ = thermal mass ($J{\cdot}K^{-1}$)
$R_t$ = thermal resistance ($K{\cdot}W^{-1}$)
$\alpha$ = thermal diffusivity ($m^2{\cdot}s^{-1}$)
$\Delta T$ = superheating; difference between wall temperature and melting temperature of phase change material (K)
$\eta_q$ = cooling power figure of merit ($J{\cdot}m^{-2}{\cdot}K^{-1}{\cdot}s^{-1/2}$)
$\rho$ = density ($kg{\cdot}m^{-3}$)
$\tau$ = thermal time constant (s)

## References


[1] White, M., Cooper, M., Chen, Y., and Bernstein, J., 2003, "Impact of Junction Temperature on Microelectronic Device Reliability and Considerations for Space Applications," IEEE International Integrated Reliability Workshop Final Report, IEEE, Lake Tahoe, CA, Oct. 20–23, pp. 133–136.
[2] Jankowski, N. R., and McCluskey, F. P., 2009, "Modeling Transient Thermal Response of Pulsed Power Electronic Packages," IEEE Pulsed Power Conference, IEEE, Washington, DC, June 28–July 2, pp. 820–825.
[3] Boteler, L. M., Miner, S. M., and Hinojosa, M., 2018, "Co-Designed High Voltage Module," 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), San Diego, CA, May 29–June 1, pp. 824–830.
[4] Mudawar, I., 2001, "Assessment of High-Heat-Flux Thermal Management Schemes," IEEE Trans. Compon. Packag. Technol., **24**(2), pp. 122–141.
[5] Zhang, P., Xiao, X., and Ma, Z. W., 2016, "A Review of the Composite Phase Change Materials: Fabrication, Characterization, Mathematical Modeling and Application to Performance Enhancement," Appl. Energy, **165**, pp. 472–510.
[6] Boteler, L., Fish, M., Berman, M., and Wang, J., 2019, "Understanding Trade-Offs of Phase Change Materials for Transient Thermal Mitigation," 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, Las Vegas, NV, May 28–31, pp. 870–877.
[7] Sharar, D. J., Donovan, B. F., Warzoha, R. J., Wilson, A. A., Leff, A. C., and Hanrahan, B. M., 2019, "Solid-State Thermal Energy Storage Using Reversible Martensitic Transformations," Appl. Phys. Lett., **114**(14), p. 143902.
[8] Lu, T. J., 2000, "Thermal Management of High Power Electronics With Phase Change Cooling," Int. J. Heat Mass Transfer, **43**(13), pp. 2245–2256.
[9] Shamberger, P. J., 2016, "Cooling Capacity Figure of Merit for Phase Change Materials," ASME J. Heat Transfer, **138**(2), p. 024502.
[10] Shao, L., Raghavan, A., Kim, G.-H., Emurian, L., Rosen, J., Papaefthymiou, M. C., Wenisch, T. F., Martin, M. M. K., and Pipe, K. P., 2016, "Figure-of-Merit for Phase-Change Materials Used in Thermal Management," Int. J. Heat Mass Transfer, **101**, pp. 764–771.
[11] Moon, H., Miljkovic, N., and King, W. P., 2020, "High Power Density Thermal Energy Storage Using Additively Manufactured Heat Exchangers and Phase Change Material," Int. J. Heat Mass Transfer, **153**, p. 119591.
[12] Kant, K., Shukla, A., and Sharma, A., 2017, "Advancement in Phase Change Materials for Thermal Energy Storage Applications," Sol. Energy Mater. Sol. Cells, **172**, pp. 82–92.
[13] Shamberger, P. J., and Bruno, N. M., 2020, "Review of Metallic Phase Change Materials for High Heat Flux Transient Thermal Management Applications," Appl. Energy, **258**, p. 113955.
[14] Shamberger, P. J., and Fisher, T. S., 2018, "Cooling Power and Characteristic Times of Composite Heatsinks and Insulants," Int. J. Heat Mass Transfer, **117**, pp. 1205–1215.
[15] Barako, M. T., Lingamneni, S., Katz, J. S., Liu, T., Goodson, K. E., and Tice, J., 2018, "Optimizing the Design of Composite Phase Change Materials for High Thermal Power Density," J. Appl. Phys., **124**(14), p. 145103.
[16] Feng, S., Zhang, Y., Shi, M., Wen, T., and Lu, T. J., 2015, "Unidirectional Freezing of Phase Change Materials Saturated in Open-Cell Metal Foams," Appl. Therm. Eng., **88**, pp. 315–321.
[17] Chintakrinda, K., Weinstein, R. D., and Fleischer, A. S., 2011, "A Direct Comparison of Three Different Material Enhancement Methods on the Transient Thermal Response of Paraffin Phase Change Material Exposed to High Heat Fluxes," Int. J. Therm. Sci., **50**(9), pp. 1639–1647.
[18] Mustaffar, A., Harvey, A., and Reay, D., 2015, "Melting of Phase Change Material Assisted by Expanded Metal Mesh," Appl. Therm. Eng., **90**, pp. 1052–1060.
[19] Sari, A., Karaipekli, A., and Kaygusuz, K., 2008, "Fatty Acid/Expanded Graphite Composites as Phase Change Material for Latent Heat Thermal Energy Storage, Energy Sources, Part a Recover," Util. Environ. Eff., **30**(5), pp. 464–474.
[20] Thiagarajan, N., De Bock, H. P. J., and Gerstler, W. D., 2016, "Thermal Management System," U.S. Patent No. 9,476,651.
[21] Thiagarajan, N., 2017, "A Novel Approach to Development of a Thermal Capacitor," Electronics Cooling, Plymouth Meeting, PA, accessed Jan. 29, 2020, https://www.electronics-cooling.com/2017/02/novel-approach-development-thermal-capacitor/
[22] Liu, X., Marbut, C., Huitink, D., Feng, G., and Fleischer, A. S., 2019, "Influence of Crystalline Polymorphism on the Phase Change Properties of Sorbitol-Au Nanocomposites," Mater. Today Energy, **12**, pp. 379–388.
[23] Zeng, J. L., Cao, Z., Yang, D. W., Sun, L. X., and Zhang, L., 2010, "Thermal Conductivity Enhancement of Ag Nanowires on an Organic Phase Change Material," J. Therm. Anal. Calorim., **101**(1), pp. 385–389.
[24] Khodadadi, J. M., and Hosseinizadeh, S. F., 2007, "Nanoparticle-Enhanced Phase Change Materials (NEPCM) With Great Potential for Improved Thermal Energy Storage," Int. Commun. Heat Mass Transfer, **34**(5), pp. 534–543.
[25] Sharma, R. K., Ganesan, P., Tyagi, V. V., Metselaar, H. S. C., and Sandaran, S. C., 2016, "Thermal Properties and Heat Storage Analysis of Palmitic Acid-$TiO_2$ Composite as Nano-Enhanced Organic Phase Change Material (NEOPCM)," Appl. Therm. Eng., **99**, pp. 1254–1262.
[26] Şahan, N., Fois, M., and Paksoy, H., 2015, "Improving Thermal Conductivity Phase Change Materials—A Study of Paraffin Nanomagnetite Composites," Sol. Energy Mater. Sol. Cells, **137**, pp. 61–67.
[27] Sahan, N., and Paksoy, H. O., 2014, "Thermal Enhancement of Paraffin as a Phase Change Material With Nanomagnetite," Sol. Energy Mater. Sol. Cells, **126**, pp. 56–61.
[28] Parameshwaran, R., Deepak, K., Saravanan, R., and Kalaiselvam, S., 2014, "Preparation, Thermal and Rheological Properties of Hybrid Nanocomposite Phase Change Material for Thermal Energy Storage," Appl. Energy, **115**, pp. 320–330.
[29] Weinstein, R. D., Kopec, T. C., Fleischer, A. S., D'Addio, E., and Bessel, C. A., 2008, "The Experimental Exploration of Embedding Phase Change Materials With Graphite Nanofibers for the Thermal Management of Electronics," ASME J. Heat Transfer, **130**(4), p. 042405.
[30] Sanusi, O., Warzoha, R., and Fleischer, A. S., 2011, "Energy Storage and Solidification of Paraffin Phase Change Material Embedded With Graphite Nanofibers," Int. J. Heat Mass Transfer, **54**(19–20), pp. 4429–4436.
[31] Teng, T.-P., Cheng, C.-M., and Cheng, C.-P., 2013, "Performance Assessment of Heat Storage by Phase Change Materials Containing MWCNTs and Graphite," Appl. Therm. Eng., **50**(1), pp. 637–644.
[32] Karaipekli, A., Biçer, A., Sarı, A., and Tyagi, V. V., 2017, "Thermal Characteristics of Expanded Perlite/Paraffin Composite Phase Change Material With Enhanced Thermal Conductivity Using Carbon Nanotubes," Energy Convers. Manag., **134**, pp. 373–381.
[33] Warzoha, R. J., and Fleischer, A. S., 2014, "Improved Heat Recovery From Paraffin-Based Phase Change Materials Due to the Presence of Percolating Graphene Networks," Int. J. Heat Mass Transfer, **79**, pp. 314–323.
[34] Li, J. F., Lu, W., Zeng, Y. B., and Luo, Z. P., 2014, "Simultaneous Enhancement of Latent Heat and Thermal Conductivity of Docosane-Based Phase Change Material in the Presence of Spongy Graphene," Sol. Energy Mater. Sol. Cells, **128**, pp. 48–51.
[35] Mehrali, M., Latibari, S. T., Mehrali, M., Metselaar, H. S. C., and Silakhori, M., 2013, "Shape-Stabilized Phase Change Materials With High Thermal Conductivity Based on Paraffin/Graphene Oxide Composite," Energy Convers. Manag., **67**, pp. 275–282.
[36] Harish, S., Orejon, D., Takata, Y., and Kohno, M., 2015, "Thermal Conductivity Enhancement of Lauric Acid Phase Change Nanocomposite With Graphene Nanoplatelets," Appl. Therm. Eng., **80**, pp. 205–211.
[37] Yu, S., Jeong, S.-G., Chung, O., and Kim, S., 2014, "Bio-Based PCM/Carbon Nanomaterials Composites With Enhanced Thermal Conductivity," Sol. Energy Mater. Sol. Cells, **120**, pp. 549–554.
[38] McKinsey, 2020, "Electrification," McKinsey, New York, accessed Jan. 29, 2020, https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview/electrification
[39] Tolbert, L. M., Ozpineci, B., Islam, S. K., and Peng, F. Z., 2002, "Impact of SiC Power Electronic Devices for Hybrid Electric Vehicles," SAE Trans., **111**, pp. 765–771.
[40] Arcus, C., 2018, "Tesla Model 3 & Chevy Bolt Battery Packs Examined," CleanTechnica, Online Media, accessed Jan. 29, 2020, https://cleantechnica.com/2018/07/08/tesla-model-3-chevy-bolt-battery-packs-examined/
[41] Zhou, P., 2010, "Electric Vehicle Thermal Management System," U.S. Patent No. 7,789,176.
[42] Kandasamy, R., Wang, X.-Q., and Mujumdar, A. S., 2008, "Transient Cooling of Electronics Using Phase Change Material (PCM)-Based Heat Sinks," Appl. Therm. Eng., **28**(8–9), pp. 1047–1057.
[43] Baby, R., and Balaji, C., 2012, "Experimental Investigations on Phase Change Material Based Finned Heat Sinks for Electronic Equipment Cooling," Int. J. Heat Mass Transfer, **55**(5–6), pp. 1642–1649.
[44] Srikanth, R., and Balaji, C., 2017, "Experimental Investigation on the Heat Transfer Performance of a PCM Based Pin Fin Heat Sink With Discrete Heating," Int. J. Therm. Sci., **111**, pp. 188–203.
[45] Harris, R. J., Leland, Q., Du, J., and Chow, L. C., 2006, "Characterization of Paraffin-Graphite Foam and Paraffin-Aluminum Foam Thermal Energy Storage Systems," AIAA Paper No. 2006-3132.
[46] Fan, L.-W., Xiao, Y.-Q., Zeng, Y., Fang, X., Wang, X., Xu, X., Yu, Z.-T., Hong, R.-H., Hu, Y.-C., and Cen, K.-F., 2013, "Effects of Melting Temperature

and the Presence of Internal Fins on the Performance of a Phase Change Material (PCM)-Based Heat Sink," Int. J. Therm. Sci., **70**, pp. 114–126.
[47] Ashraf, M. J., Ali, H. M., Usman, H., and Arshad, A., 2017, "Experimental Passive Electronics Cooling: Parametric Investigation of Pin-Fin Geometries and Efficient Phase Change Materials," Int. J. Heat Mass Transfer, **115**, pp. 251–263.
[48] Arshad, A., Ali, H. M., Khushnood, S., and Jabbal, M., 2018, "Experimental Investigation of PCM Based Round Pin-Fin Heat Sinks for Thermal Management of Electronics: Effect of Pin-Fin Diameter," Int. J. Heat Mass Transfer, **117**, pp. 861–872.
[49] Dede, E. M., Joshi, S. N., and Zhou, F., 2015, "Topology Optimization, Additive Layer Manufacturing, and Experimental Testing of an Air-Cooled Heat Sink," ASME J. Mech. Des., **137**(11), p. 111403.
[50] Zhou, M., Alexandersen, J., Sigmund, O., and Pedersen, C. B. W., 2016, "Industrial Application of Topology Optimization for Combined Conductive and Convective Heat Transfer Problems," Struct. Multidiscip. Optim., **54**(4), pp. 1045–1060.
[51] de Bock, H. P., 2018, "Exploration of a Hybrid Analytical Thermal Topology Optimization Method for an Additively Manufactured Heat Sink," 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, San Diego, CA, 29 May–1 June, pp. 761–767.
[52] Iradukunda, A.-C., and Huitink, D., 2019, "Topology Optimized Fins for a PCM-Based Thermal Management System," 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, Las Vegas, NV, May 28–31, pp. 1001–1005.
[53] Guterl, F., 2019, "That's Hot—This Lung-Inspired 3D-Printed Part for Cooling $CO_2$ Could Take Power Generation to the Next Level," General Electric, Boston, MA, accessed Jan. 29, 2020, https://www.ge.com/reports/thats-hot-this-lung-inspired-3d-printed-part-for-cooling-co2-could-take-power-generation-to-the-next-level/
[54] Gerstler, W. D., and Erno, D., 2017, "Introduction of an Additively Manufactured Multi-Furcating Heat Exchanger," 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, Orlando, FL, May 30–June 2, pp. 624–633.
[55] Jackson, S., Palazotto, A., Pachter, M., and Niedbalski, N., 2019, "Control of Vapor Compression Cycles Under Transient Thermal Loads," AIAA Paper No. 2019-0536.
[56] Yang, Z., Pollock, D. T., and Wen, J. T., 2017, "Optimization and Predictive Control of a Vapor Compression Cycle Under Transient Pulse Heat Load," Int. J. Refrig., **75**, pp. 14–25.
[57] Walters, E., Amrhein, M., O'Connell, T., Iden, S., Lamm, P., Yerkes, K., Wolff, M., McCarthy, K., Raczkowski, B., and Wells, J., 2010, "INVENT Modeling, Simulation, Analysis and Optimization," AIAA Paper No. 2010-287.
[58] McCarthy, P. T., McCarthy, K., Hasan, M., Boyd, M., Chang, M., Walters, E., and Niedbalski, N., 2019, "A Multi-Domain Component Based Modeling Toolset for Dynamic Integrated Power and Thermal System Modeling," SAE Paper No. 2019-01-1385.
[59] Kania, M., Koeln, J., Alleyne, A., McCarthy, K., Wu, N., and Patnaik, S., 2012, "A Dynamic Modeling Toolbox for Air Vehicle Vapor Cycle Systems," SAE Paper No. 2012-01-2172.
[60] McCarthy, P., Niedbalski, N., McCarthy, K., Walters, E., Cory, J., and Patnaik, S., 2016, "A First Principles Based Approach for Dynamic Modeling of Turbomachinery," SAE Int. J. Aerosp., **9**(1), pp. 45–61.
[61] Nafis, B. M., Iradukunda, A., and Huitink, D., 2018, "Drive Schedule Impacts to Thermal Design Requirements and the Associated Reliability Implications in Electric Vehicle Traction Drive Inverters," ASME Paper No. IPACK2018-8280.
[62] Huitink, D., 2017, "Thermomechanical Reliability Challenges and Goals and Design for Reliability Methodologies for Electric Vehicle Systems," ASME Paper No. IPACK2017-74245.
[63] Ciappa, M., 2002, "Selected Failure Mechanisms of Modern Power Modules," Microelectron. Reliab., **42**(4–5), pp. 653–667.
[64] Czyż, P., 2015, "Performance Evaluation of a 650V E-HEMT GaN Power Switch," IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society, IEEE, Yokohama, Japan, Nov. 9–12, pp. 7–12.
[65] Omura, I., Saito, W., Domon, T., and Tsuda, K., 2007, "Gallium Nitride Power HEMT for High Switching Frequency Power Electronics," International Workshop on Physics of Semiconductor Devices, Mumbai, India, Dec. 16–20, pp. 781–786.
[66] Boutros, K. S., Chandrasekaran, S., Luo, W. B., and Mehrotra, V., 2006, "GaN Switching Devices for High-Frequency, KW Power Conversion," IEEE International Symposium on Power Semiconductor Devices and IC's, IEEE, Naples, Italy, June 4–8, pp. 1–4.
[67] Lundh, J. S., Chatterjee, B., Song, Y., Baca, A. G., Kaplar, R. J., Beechem, T. E., Allerman, A. A., Armstrong, A. M., Klein, B. A., Bansal, A., Talreja, D., Pogrebnyakov, A., Heller, E., Gopalan, V., Redwing, J. M., Foley, B. M., and Choi, S., 2019, "Multidimensional Thermal Analysis of an Ultrawide Bandgap AlGaN Channel High Electron Mobility Transistor," Appl. Phys. Lett., **115**(15), p. 153503.
[68] Dallas, J., Pavlidis, G., Chatterjee, B., Lundh, J. S., Ji, M., Kim, J., Kao, T., Detchprohm, T., Dupuis, R. D., Shen, S., Graham, S., and Choi, S., 2018, "Thermal Characterization of Gallium Nitride P-i-n Diodes," Appl. Phys. Lett., **112**(7), p. 073503.
[69] Beechem, T. E., McDonald, A. E., Fuller, E. J., Talin, A. A., Rost, C. M., Maria, J.-P., Gaskins, J. T., Hopkins, P. E., and Allerman, A. A., 2016, "Size Dictated Thermal Conductivity of GaN," J. Appl. Phys., **120**(9), p. 095104.
[70] Chatterjee, B., Zeng, K., Nordquist, C. D., Singisetti, U., and Choi, S., 2019, "Device-Level Thermal Management of Gallium Oxide Field-Effect Transistors," IEEE Trans. Compon., Packag. Manuf. Technol., **9**(12), pp. 2352–2365.
[71] Bergman, T. L., Incropera, F. P., DeWitt, D. P., and Lavine, A. S., 2011, *Fundamentals of Heat and Mass Transfer*, Wiley, Hoboken, NJ.
[72] Rais-Zadeh, M., Gokhale, V. J., Ansari, A., Faucher, M., Théron, D., Cordier, Y., and Buchaillot, L., 2014, "Gallium Nitride as an Electromechanical Material," J. Microelectromech. Syst., **23**(6), pp. 1252–1271.
[73] Zhao, Y., Zhu, C., Wang, S., Tian, J. Z., Yang, D. J., Chen, C. K., Cheng, H., and Hing, P., 2004, "Pulsed Photothermal Reflectance Measurement of the Thermal Conductivity of Sputtered Aluminum Nitride Thin Films," J. Appl. Phys., **96**(8), pp. 4563–4568.
[74] Daly, B. C., Maris, H. J., Nurmikko, A. V., Kuball, M., and Han, J., 2002, "Optical Pump-and-Probe Measurement of the Thermal Conductivity of Nitride Thin Films," J. Appl. Phys., **92**(7), pp. 3820–3824.
[75] Nipko, J. C., and Loong, C.-K., 1998, "Phonon Excitations and Related Thermal Properties of Aluminum Nitride," Phys. Rev. B, **57**(17), pp. 10550–10554.
[76] Bonner, R. W., Desai, T., Gao, F., Tang, X., Palacios, T., Shin, S., and Kaviany, M., 2011, "Die Level Thermal Storage for Improved Cooling of Pulsed Devices," 27th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, IEEE, San Jose, CA, Mar. 20–24, pp. 193–197.
[77] Soupremanien, U., Szambolics, H., Quenard, S., Bouchut, P., Roumanie, M., Bottazzini, R., and Dunoyer, N., 2016, "Integration of Metallic Phase Change Material in Power Electronics," 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, Las Vegas, NV, May 31–June 3, pp. 125–133.
[78] Gonzalez-Nino, D., Boteler, L. M., Ibitayo, D., Jankowski, N. R., Urciuoli, D., Kierzewski, I. M., and Quintero, P. O., 2018, "Experimental Evaluation of Metallic Phase Change Materials for Thermal Transient Mitigation," Int. J. Heat Mass Transfer, **116**, pp. 512–519.
[79] Bar-Cohen, A., and Wang, P., 2009, "On-Chip Hot Spot Remediation With Miniaturized Thermoelectric Coolers," Microgravity Sci. Technol., **21**(S1), pp. 351–359.
[80] Green, C. E., Fedorov, A. G., and Joshi, Y. K., 2012, "Dynamic Thermal Management of High Heat Flux Devices Using Embedded Solid-Liquid Phase Change Materials and Solid State Coolers," 13th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, San Diego, CA, May 30–June 1, pp. 853–862.
[81] Boteler, L., Berman, M., Miner, S., and Fish, M., "ARL ParaPower," U.S. Army Research Laboratory, Adelphi, MD, accessed Jan. 29, 2020, https://github.com/USArmyResearchLab/ParaPower
[82] Boteler, L., and Smith, A., 2013, "3D Thermal Resistance Network Method for the Design of Highly Integrated Packages," ASME Paper No. HT2013-17575.
[83] Boteler, L. M., and Miner, S. M., 2017, "Power Packaging Thermal and Stress Model for Quick Parametric Analyses," ASME Paper No. IPACK2017-74130.
[84] Boteler, L. M., and Miner, S. M., 2018, "Comparison of Thermal and Stress Analysis Results for a High Voltage Module Using FEA and a Quick Parametric Analysis Tool," ASME Paper No. IPACK2018-8394.
[85] Deckard, M., Shamberger, P., Fish, M., Berman, M., Wang, J., and Boteler, L., 2019, "Convergence and Validation in ParaPower: A Design Tool for Phase Change Materials in Electronics Packaging," 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, Las Vegas, NV, May 28–31, pp. 878–885.