Letters

A Review of Select Patented Technologies for Cooling of High Heat Flux Power Semiconductor Devices

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***Abstract*—The development of wide band-gap power electronics over the last two decades has stimulated a tremendous amount of research into high-performance liquid cooling solutions for high heat flux (200–1000 W/cm^2) power semiconductor devices. A patent literature search for electronics cooling technologies was conducted in the late-2000 time frame and promising technologies for high-performance thermal management were identified, at that time, for research and development. These promising technologies were separated into four categories classified as single-phase (i.e., liquid) jet impingement cooling, microchannel cooling, phase change or two-phase cooling, and near-junction including direct chip cooling. In this letter, a perspective is provided on select patents from our group that stems from research into these technology areas from 2010 to 2022. Additionally, the thermal-fluid performance capability of each technology is briefly summarized. As a whole, the letter provides a demonstration of the historical significance of power electronics cooling technology on the mobility industry and briefly outlines future directions for research and development.**

***Index Terms*—Cold plate, embedded, near-junction, power electronics, single-phase, thermal management, topology optimization, two-phase (2-ϕ).**

I. Introduction

In THE late-2000 time frame, an eventual transition was anticipated by mobility companies to shift away from silicon (Si) power semiconductor devices, such as insulated gate bipolar transistors [1], [2], toward next-generation wide band-gap (WBG) power devices, such as metal–oxide–semiconductor field-effect transistors (MOSFETs). The United States (U.S.) Department of Energy (DOE) led research organizations such as the Vehicle Technologies Office (VTO) and Advanced Research Projects Agency–Energy that have played an imperative role in power electronics innovation [3], [4]. Ambitious technical targets and various funding opportunities sparked innovation across broad fields ranging from materials to system integration in order to push current technological limits. Programs associated with WBG devices and applications undoubtedly contributed to the exploration of enabling technologies and establishing a firm foundation for a high power density electronics ecosystem [5]. Today, different WBG semiconductor materials have been developed such as gallium nitride [6], [7], silicon carbide (SiC) [8], [9], diamond, and gallium oxide [10], [11]. These materials enable power electronics that exhibit higher possible switching frequencies, reduced switching losses, smaller passive sizes, and greater operational temperatures. These performance benefits nonetheless lead to technical challenges associated with the control of the power device itself, subsequent circuit response, temperature capability of package materials [12], and cooling of packages plus devices having higher power density [13], [14], [15]. Therefore, in the same late-2000 period, a comprehensive patent literature search for electronics cooling technologies was conducted to understand established approaches, the latest state of the art, and possible future research directions.

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TABLE I
Seven Technical Categories for the Electronics Cooling Technology U.S. Patent Literature Survey Spanning 1976 to 2009

	Technical category	Prior art
1	Traditional finned structures	[16], [17]
2	Fluid jet impingement devices	[18], [19], [20]
3	Porous metal foam (MF) materials	[21], [22], [23]
4	Lattice or cellular (e.g., honeycomb) structures	[24], [25], [26]
5	Microchannel or microstructure-based devices	[27], [28], [29]
6	Boiling, condensation, or evaporation devices	[30], [31], [32], [33]
7	Direct cooling of a chip	[18], [27], [33]

Note: Representative prior art is additionally provided.

At the time, the U.S. patent survey that was performed considered granted patents and applications spanning the years 1976 to 2009. The survey was based off of a keyword search that included seven primary technical areas, as shown in Table I. The prior art patent search produced 529 granted patents and 435 patent applications totaling 964 patents over the specified 33-year time range. A breakdown of the number of patents and applications by technical category is provided in Fig. 1, and some representative prior art is referenced in Table I. The four technology categories highlighted in Fig. 1 were selected in 2010 based on 1) impactful surveys from experts in the field, e.g., [34] and 2) our distilled interpretation of the most promising high-performance cooling technologies for a range of relevant power electronics device heat fluxes, as illustrated in Fig. 2. Specifically, liquid jet impingement in combination with microchannels, two-phase (2-ϕ) cooling, and direct/embedded (near-junction) cooling were identified to be most promising for cooling high heat flux WBG devices. This letter outlines patented technologies spanning 2010–2022 that were then developed from an understanding of this technology landscape. Note that research literature from other groups since 2010 shows similar focus on high heat flux thermal management studies using jets/microchannels [35], [36], [37], 2-ϕ cooling [38], [39], [40], and near-junction approaches [41], [42], [43], [44]. However, given the patent-related scope of this letter, we focus on ideas stemming from our research group.

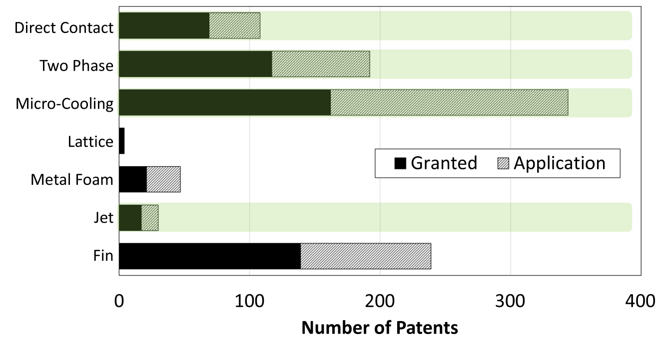

Fig. 1. Breakdown of electronics cooling technology U.S. patent literature prior art into seven technical categories, as per Table I; data are from granted patents and patent applications from 1976 to 2009. The highlighted categories in green indicated opportunities, at the time of the search, for high-performance cooling technology research and development. This search motivated the select patented technologies spanning 2010–2022 presented in this letter.

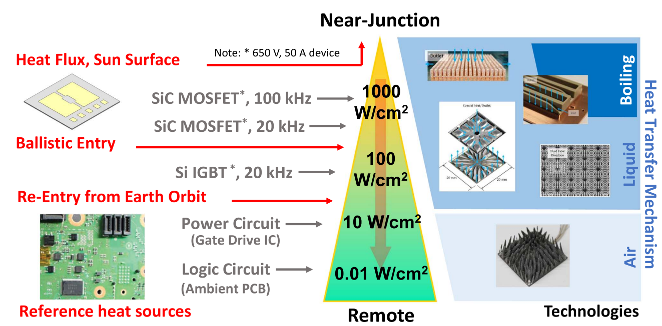

Fig. 2. Heat fluxes for various power electronics devices at different physical scales ranging from logic/power circuit to SiC MOSFET (on the left side) and mapped to cooling technology or approach (on the right side). Liquid jet impingement, 2-ϕ cooling, and direct/embedded (near-junction) cooling are most promising for high heat flux WBG devices.

II. Single-Phase Cooling

As reviewed extensively in [45], single-phase liquid cold plate (i.e., cooler) technologies for thermal management of electronics may include fluid flow through microchannels or fluid jet impingement. Microchannels provide a high heat transfer rate, although with a large pressure drop, and buildup of a thermal boundary layer within long channels is unavoidable. In contrast, jet impingement typically requires less fluid pumping power while enabling moderate heat transfer. Thus, optimal liquid cooling solutions may employ both concepts simultaneously, and two representative examples are shown schematically in Fig. 3(a) and (b) with respective patents [46] and [47], and detailed illustrations in Figs. 4 and 5. The cold plate shown schematically in Fig. 3(a) and in detail in Fig. 4 is a multipass microchannel design that utilizes six unit cells in a 2×3 array for the cooling of six power semiconductor devices. Coolant travels through a manifold layer optimized to provide uniform fluid flow to each unit cell. As illustrated in Fig. 3(a), the coolant in each unit cell then passes through a center jet, impinges the center of the heated package [e.g., direct-bond-copper (DBC) plus power device], flows radially outward through cold plate microchannels toward the edges of the package, and then moves through a second pass of microchannels while traveling radially inwards. The microchannel layout in each layer of the unit cell is also designed using an innovative thermal-fluid topology optimization approach [48] to balance flow resistance with heat transfer. This represents a first such thermal-fluid topology optimization work targeted toward the cooling of electronics, as discussed in a recent independent review of the field (see [49, Table 5]). Favorable convective heat transfer due to multiple heat transfer passes with relatively low pressure drop [50] is an advantage for this aluminum cold plate when compared with standard straight channel designs that were common to the industry in the 2010 time frame [51] (refer to Table II); note that the definition for variables is provided in the Appendix. A disadvantage of the multipass cold plate design is the diffusion bonding process that requires precise surface finishes and fits

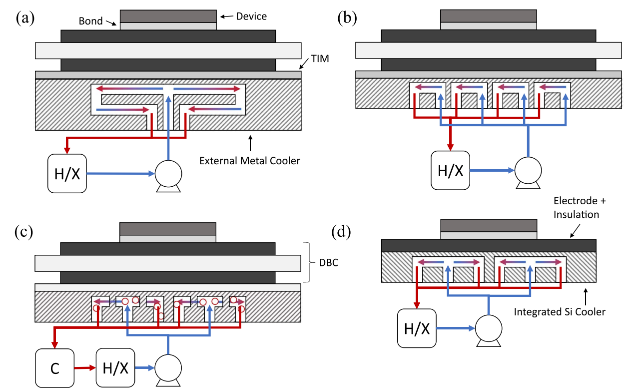

Fig. 3. Power electronics package schematics to illustrate possible integration and the working principle for cold plate designs. (a) Multipass cold plate with center jet plus two microchannel passes. (b) MMC cold plate utilizes multiple slot jets into and out of straight fins (running parallel to the page). (c) 2-ϕ cooling with multiple jets impinging a porous coated pin fin surface. (d) Near-junction cooling with jets and microchannels embedded in a Si wafer for direct die attach. Note: C = condenser; DBC = direct-bond-copper substrate; H/X = heat exchanger; TIM = thermal interface material.

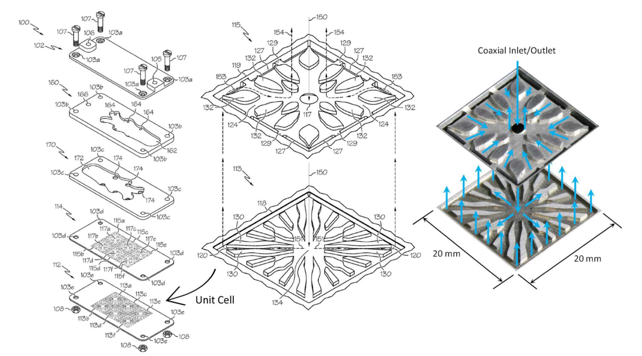

Fig. 4. Multipass branching microchannel power electronics cold plate designed using multiphysics (single-phase, thermal-fluid) topology optimization; images adapted from [46]. Fabricated two-pass structure shown on the right.

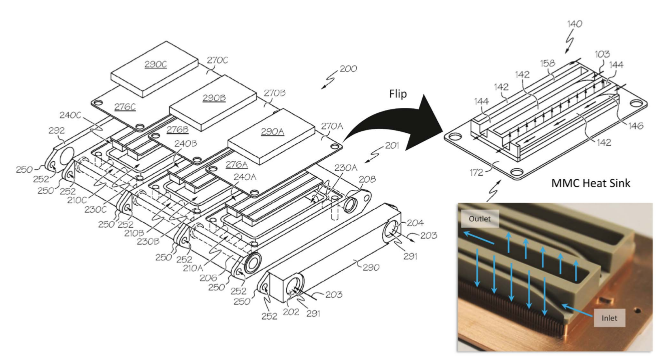

Fig. 5. Modular hybrid slot jet and minichannel MMC single-phase power electronics cooler; images adapted from [47]. Image on the lower right highlights a fabricated MMC heat sink.

TABLE II
NORMALIZED PERFORMANCE INDICATORS[1,2]

Cooling technology	h	ΔP	$\dot{v}$
Straight channel◇ [51]	1	1	1
Multi-pass◇ [50]	2.23	0.50	1.00
MMC† [53]	3.38	0.54	1.33
2-ϕ§ [54]	9.80	0.46	1.08
Near-junction‡ [55]	10.00	2.20	0.50

[1] Refer to the appendix for indicator (i.e., variable) definitions; each indicator is normalized relative to the corresponding performance index of a representative straight channel cold plate.
[2] Performance based on cooling six-device power module [56], [57].
◇ 50/50 ethylene-glycol/water coolant at $T_{\rm in} = 65°$C
† 50/50 ethylene-glycol/water coolant at $T_{\rm in} = 105°$C
§ Refrigerant R-245fa coolant at $T_{\rm in} = 40°$C
‡ Deionized water coolant at $T_{\rm in} = 50°$C

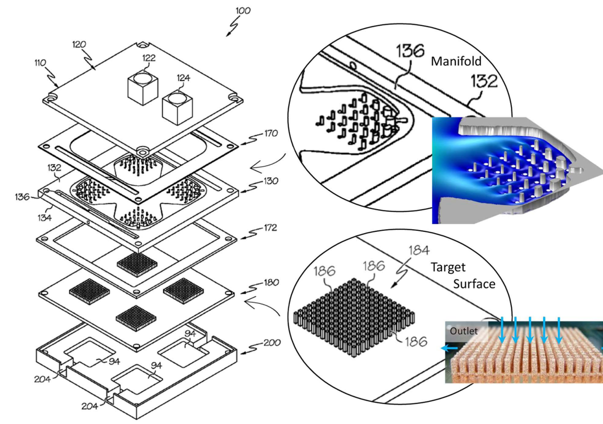

Fig. 6. Compact cold plate manifold and heat sink for 2-ϕ cooling of power electronics; images adapted from [63].

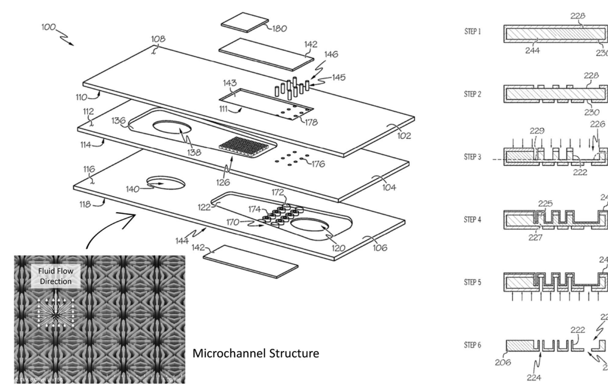

Fig. 7. Unit cell microchannel with jet impingement cooling chip (left); image adapted from [64]. Representative dual-side DRIE fabrication process for a single layer of the cooling chip (right); image adapted from [68].

to realize a monolithic cooler [50], although other methods such as additive manufacturing might instead be employed [52].

Figs. 3(b) and 5, respectively, illustrate the working principle and details of a different modular design for a single-phase manifold mini/microchannel (MMC) cold plate [53] developed as part of a U.S. DOE VTO national project. This design also combines the favorable performance of a liquid jet with microchannel flow through intelligent 3D structuring with a manifold. Specifically, an MMC cooler operates by providing numerous slot jets that impinge between the straight fins of a heat sink and exit quickly in the opposite direction of the jets [see Fig. 3(b)], leading to low pressure drop and reduced thermal boundary layer effects [58]. In Fig. 5, a geometrically optimized manifold is paired with a copper heat sink to realize the MMC function leading to high convective cooling performance, as shown in Table II. Innovative advantages described in [47] and [53] are twofold. First, the cold plate flow structure is modular and may be easily customized to accommodate a greater or smaller number of power modules. Second, the coolant flow path is reconfigurable, which enables different thermal-fluid (i.e., heat transfer and pressure drop) capabilities to be realized with the same design. A disadvantage of the concept is that the number of components required for a full cold plate assembly rapidly increases for a system comprising numerous power modules.

III. 2-ϕ COOLING

Single-phase liquid-cooled cold plates and air-cooled heat sinks are commonly used to tackle the thermal management challenges of power electronics. To handle device power densities greater than 1000 W/cm^2 in a compact space, advanced technologies, employing 2-ϕ heat transfer, may be required. A compact cooler was designed based on a submerged fluid jet impingement approach with the following advantages: higher single-phase performance, higher 2-ϕ performance in terms of critical heat flux, and lower pressure drop, as reported in extensive studies [54], [59], [60], [61]. Some key enablers to achieve high performance include optimization techniques for greater flow uniformity [62] and the use of a multiscale, optimized porous surface [54], [60] to achieve enhanced 2-ϕ performance. A representative patent that implements these features is described in [63] with working principle illustrated in Fig. 3(c) and design details shown in Fig. 6. For this cooler, multiple fluid jets impinge a porous-coated pin fin structure for an enhanced surface area that promotes bubble nucleation. Thus, as an innovative advantage, the 2-ϕ submerged jet impingement cold plate combines the above strategies to realize an extremely high heat transfer coefficient [54], 98 000 W/(m$^2 \times$ K), with low pressure drop, 4.6 kPa at 0.45 l/min coolant volumetric flow rate per device, in a compact, 48 × 48 × 10 mm^3, size. Table II provides the thermal-fluid performance relative to other cooling technologies. Drawbacks of this technology include vapor flow instabilities plus associated cooler orientation effects inherent in 2-ϕ systems (although these are somewhat mitigated by the forced jet approach). Additionally, a condenser, labeled as the component "C" in Fig. 3(c), is an additional flow loop component required for vapor exiting the cooler.

IV. NEAR-JUNCTION COOLING

The reduction of the cumulative thermal resistance of conductive components between the heat source and coolant, e.g., cold plate, TIM, and electrical isolation material, is one of the primary strategies for cooling enhancement. The most aggressive way to maximize cooling is to eliminate these conductive thermal resistances, i.e., immersion cooling. However, for electrical isolation purposes, the working fluid must be a dielectric that leads to higher convective thermal resistance. To enable a broader selection of coolants and simultaneously minimize conductive thermal resistance, extensive research has been conducted on Si-based near-junction cooling for power electronics. The attachment of a separate chip-scale Si-based cooler to the power device, as shown schematically in Fig. 3(d), can significantly simplify integration while providing electrical isolation and flexibility for an optimized cooling structure. The experimental results in [55] demonstrate the high convective cooling performance achievable using this approach. In Fig. 7, a 20 × 10 × 1.47 mm^3 cooling chip is shown that is capable of dissipating up to 1.02 kW/cm^2 heat flux over a 0.25 cm^2 actively cooled area. The cooling chip contains an array of internal fluid jets. Each jet impinges a corresponding unit cell of microchannels with an innovative design again based on thermal-fluid topology optimization; refer to the microchannel structure shown in the lower left image of Fig. 7 and the schematic of the working principle in Fig. 3(d), and [55] and [64] for greater details. The maximum average heat transfer coefficient reaches 120.2 kW/(m$^2\times$ K). A similar design for lower pressure drop application is presented in [65] with a related thermal and manufacturing study in [66]. Alternative chip-scale cooler designs are further found in [64] and [67]. The detailed deep reactive ion etching (DRIE) process for multilayer Si-based cooler fabrication is described in [68]. Performance relative to the other cooling technologies at a select operational point from [55] is shown in Table II. Despite high thermal performance, large pressure drop and potential microchannel clogging are drawbacks for near-junction cooling even with efforts to optimize the fluid flow path. Additionally, a somewhat complicated multiwafer etching and bonding process is a disadvantage of the design in Fig. 7, although new design and process innovations [69] may enable a path toward commercialization for related wafer-based near-junction coolers [70].

V. Conclusion

In this letter, we reviewed patents from 2010 to 2022 stemming from sustained research into select power semiconductor device cooling technology areas. These technologies exploit liquid jet impingement in combination with microchannels, 2-ϕ heat transfer, and near-junction cooling. Results indicate a trend toward progressively higher convective heat transfer. As lower convective thermal resistance is realized, effort must be placed on commensurate reductions in the conductive thermal resistance of the package to accommodate continuously increasing device heat fluxes. The single-phase and 2-ϕ cooling technologies introduced here are highly scalable to different size power systems for harsh environments. The scalability and adoption of near-junction cooling is logically more dependent on a specific power module package. Thus, future research and development may focus on novel techniques for integration of aggressive single- or two-phase cooling into the electronics package close to the junction. Associated continued research into pumping power reduction and reliability for near-junction cooling is critical. Product implementation of advanced cooling techniques should be regularly considered and balanced with system-level requirements and complexity. Nonetheless, high performance and efficient cooling of electronics will continue to enable a range of next-generation mobility-related power conversion applications.

Appendix

The cold plate heat transfer coefficient is defined as $h = Q/[A_d(T_s - T_{\text{in}})]$, where Q is the power of the device (i.e., representative heater power corrected for heat loss), A_d is the device footprint area, T_s is the cold plate surface temperature, and T_{in} is the fluid inlet temperature. The cold plate pressure drop is $\Delta P = P_{\text{in}} - P_{\text{out}}$, where P_{in} and P_{out} are the measured inlet and outlet pressures, respectively, at a coolant volumetric flow rate $\dot{v}$.

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