

Active Heat Sink for Automotive Electronics

John Vetrovec

Aqwest LLC

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ABSTRACT

This paper reports an active heat sink (AHS) that allows high-density electronic components to operate at a stable temperature over a broad range of ambient conditions. AHS receives heat at high flux and transfers it at reduced flux to environment, coolant fluid (e.g., air or engine coolant), or structures. Temperature of the heat load can be controlled electronically. Target applications for AHS include thermal management of the new class of high-power electronics being developed for electric hybrid vehicles. AHS also enables precise control over junction temperature (and, thus, light color) of high-power light-emitting diodes (LED) used for solid-state headlights and allows for compact air-cooled heat sinks. Depending on the configuration, AHS thermal resistance can be as low as 0.1 degC/W. AHS physics, engineering design, and performance simulations are presented.

INTRODUCTION

As electronics become more miniaturized, the removal of heat often becomes the limiting factor and a barrier to further performance enhancements [1,2]. Automotive application presents a particularly challenging thermal environment for semiconductor electronics, including large temperature swings and vibrations. This challenge is compounded by ongoing miniaturization of digital and analog devices requiring a removal of heat at ever increasing fluxes. Traditional heat sinks and heat spreaders have large thermal impedance contributing to elevated junction temperatures and reduced device reliability [3].

Thermal management is of particular importance in hybrid electric vehicles (HEV) and future plug-in hybrid electric vehicles (PHEV). Needed improvements include a heat transfer boost for high-current semiconductors, elimination of hot spots, and reduction of volume, while allowing for high-current density. Suitable technologies should offer low thermal resistance, close matches between the coefficients of thermal expansion (CTE) of the semiconductor and packaging materials, and temperature control.

The overall objective in these applications is to eliminate extra cooling loops that complicate the design and reduce reliability. Preferably, existing loops from the engine, through the radiator, would be used to cool the power electronics. In this scenario, the coolant may reach temperatures as high as 105°C at the inlet to the power electronics. To avoid the semiconductor junction operating at excessive temperatures and, thus, compromising reliability, thermal resistance from the junctions to the coolant must be minimized. Alternatively, air-cooled heat sinks may be used. The challenge in this scenario is to stabilize the semiconductor temperature in view of the air temperature variations from freezing ambient levels to nearly 80°C under the hood. As a further complication, existing packaging technologies for the electronics in these advanced vehicles suffer from reliability issues, which are made more severe by long-term thermal and power cycling. Because of the elevated operational temperatures anticipated for the power electronics in HEVs and PHEVs, a pressing need exists for reliable, low-cost, high-temperature packaging.

LIMITATIONS OF CURRENT TECHNOLOGIES

Thermal management of high-power semiconductors presents three (3) challenges: 1) removal and spreading of the high-flux waste heat from the junctions, 2) transfer of waste heat to the primary thermal management system, and 3) providing temperature control. A typical thermal management system for high-power electronics includes heat acquisition means, heat transport, and a primary heat exchanger (HEX), which may be an automotive radiator, Figure 1. The heat acquisition device can be an interface material, substrate, heat spreader, HEX, or a combination of these. Acquired heat can be transported to the primary HEX by a variety of means such as a thermal conductor, a heat pipe, liquid-based convective loop, vapor compression loop, or thermoelectric cooler. Figure 2 shows the capabilities of selected heat acquisition technologies.

Active coolers for high-heat flux components include liquid-cooled microchannels, liquid impingement jets, and evaporative sprays. Microchannels, jets, and sprays usually require dedicated (secondary) cooling loops with low viscosity, highly filtered, ultra-pure coolant, pumps/compressors, secondary HEXs to interface the primary cooling loop, and significant interconnect plumbing. The electronics temperature can be controlled by varying the coolant flowrate and/or temperature. Conventional active coolers are often complex, costly, bulky, heavy, and susceptible to leaks and freezing, making them less attractive for automotive applications.

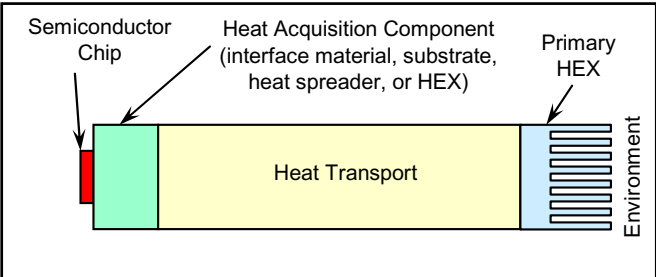


Figure 1: Typical thermal management system for high-power electronics

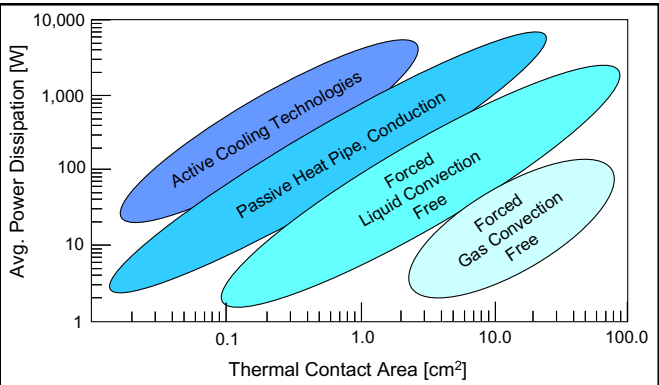


Figure 2: Capability ranges of various heat acquisition technologies (after [1])

Heat spreaders are passive components made of materials with very high thermal conductivity and adapted to receive a very high flux over a smaller area and “spread” it over a larger area, thereby reducing the heat flux to the transport means. Heat spreaders can be advantageously used with air-cooled HEXs, microchannel coolers, jet impingement coolers, heat pipes, or thermoelectric coolers (TEC) to further reduce the heat flux at the component interface. A heat spreader should have a CTE closely matched to that of the semiconductor substrate (e.g., Si and SiC). Candidate materials for constructing heat spreaders are listed in Figure 3.

Material	Thermal Conductivity [W/m-°C]	CTE [x10 ⁻⁶ /°C]
Aluminum	237	23.1
Aluminum Nitride	170	4.6
Beryllia	250	6.4
Copper	401	16.5
Copper Tungsten (90/10)	170	6.5
CVD Diamond	500-1300	2
Graphite Fiber K1100	1100	~1
Molybdenum	137	4.8
Silicon	149	2.6
Silicon Carbide	145-350	2.45

Figure 3: Selected candidate materials for heat spreaders

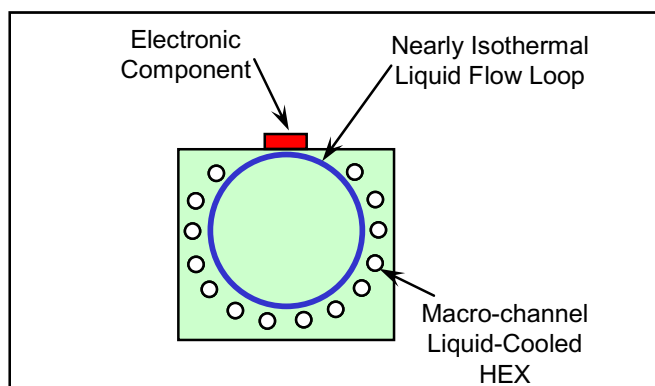
A diamond heat spreader formed by chemical vapor deposition (CVD) with thermal conductivity up to 1,300 W/m-°C is favored for many high-end applications. However, forming reliable bonds with a CVD diamond remains problematic. While passive heat spreaders are simple and generally inexpensive, they do not allow for close temperature control. In conclusion, conventional passive and active technologies (and their various combinations) offer limited performance for cooling of high-power semiconductors in automotive applications.

ACTIVE HEAT SINK CONCEPT

Aqwest is developing a novel high-performance active heat sink (AHS) technology for thermal management of high-power semiconductors offering unparalleled capabilities in high-heat flux handling and temperature control. In particular, AHS delivers these major benefits:

- Provides interface between a localized heat source and primary (system) coolant loop
- Heat spreading
- Heat flux handling >1,200 W/cm²
- Handles 100's of W of heat per unit
- Temperature control to <±1°C
- Response time <1 second
- Compatible with automotive environments

AHS solves three (3) problems in one device: 1) effective removal/spreading of waste heat from the semiconductor material, 2) transfer of waste heat to primary thermal management system, and 3) temperature control. AHS can be made from materials to match the CTE of the semiconductor material. In contrast to a purely conductive heat transfer, AHS transfers heat with a very little thermal resistance. AHS is simple, robust, and requires very low electric power to operate. Figures 5 and 6 show exemplary AHS configurations interfacing directly with liquid primary coolant (e.g., engine coolant) and air, respectively.



CONVECTIVE LIQUID LOOP – AHS has a body made of material having good thermal conductivity and preferably matched to the semiconductor substrate material CTE. Depending on application, suitable materials include Cu, Cu-W, Mo, Al, or SiC. The body

The diagram shows a central light green circle representing the 'Electronic Component'. This component is surrounded by a blue ring, which is labeled 'Nearly Isothermal Liquid Flow Loop'. The entire assembly is enclosed within a larger light green circle, which is labeled 'Finned Air-Cooled HEX'. Numerous green rectangular fins radiate outwards from the central assembly, representing the heat exchanger's cooling surface. Arrows point from the text labels to their respective parts in the diagram.

AHS body has an annular cavity with a constant radius (R_L) typically 5-20 mm and a rectangular cross-section, approximately 0.3-1 mm high. The width of the cross-section is approximately 3-10 mm as appropriate to accommodate one or more semiconductor dies. The cavity is filled with a liquid coolant and positioned so that the conduction path from the junction to the coolant is as short as possible, typically 0.2-0.5 mm.

Suitable coolants are liquids with good thermal and electrical conductivities, low viscosity, and a low freezing point. Preferred coolants for high-heat flux applications are liquid metals and their eutectic alloys. Figure 7 lists selected candidate coolants for AHS.

Parameter	Units	Coolant		
		Water (reference)	Galinstan	Gallium (Ga)
Melting Point	°C	0	-19	30
Thermal Conductivity	W/m-°C	0.598	16.5	40.6
Density	kg/m ³	998	6,440	5,910
Dynamic Viscosity	Ns/m ²	10.0 x 10 ⁻⁴	24 x 10 ⁻⁴	18 x 10 ⁻⁴
Kinematic Viscosity	m ² /s	10.0 x 10 ⁻⁷	3.73 x 10 ⁻⁷	3.0 x 10 ⁻⁷
Specific Heat	kJ/kg-°C	4.183	~0.3	0.371
Prandtl No.	-	7.0	0.044	0.016

A non-toxic eutectic liquid metal alloy known as “galinstan” (68.5% gallium, 21.5% indium, and 10% tin) is particularly attractive because of its relatively high thermal conductivity (~30 times higher than water), low