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APPLICATION OF HIGH-FLUENCE CONVECTIVE COOLING TO PULSED POWER COMPONENTS*

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Abstract

Cooling of high-energy high-power components by immersion in water or by circulating water within them is common. A major advance in cooling of VLSI substrates[1] by water under laminar flow within microchannels has started to be integrated into a number of practical subsystems[2,3]. By increasing the fluid velocity in a microchannel the convective heat transfer coefficient increases significantly when fluid flow changes from laminar to fully developed turbulence. While the higher convective heat transfer coefficient, which implies greater heat transfer and higher performance for the device being cooled, the means and mechanical design to achieve fully developed turbulence differ from the laminar systems[1,2,3]. The major differences include fluid pressure, pressure drop per unit length, channel aspect ratio, heat-sink material properties, and thermal expansion compatibility to substrates. These differences are discussed in the context of a design example for a 1,180 W/cm^2 micro-channel heat sink applied to an IGBT module.

I. INTRODUCTION

The pioneering work of Tuckerman and Pease[1] on laminar-flow microchannel cooling has started to find application in an insulated gate bipolar transistor, IGBT, module[2] and a laser diode module[3]. Weisberg *et al*[4] discuss the power dissipation per unit area, P/A, and optimization of high-aspect ratio channels for devices operating in the laminar flow regime. A further increase in cooling is possible by increasing the fluid flow to materially increase mass transport through a device and to achieve fully developed turbulence, which significantly increases the convective heat transfer rate, h_c, at the fluid-to-channel wall interface[5].

While increasing the fluid pressure, p, increases P/A, the higher pressure implies a requirement for additional wall thickness due to greater tensile loading. For maximum heat transfer from a device to a micro-channel heat sink, however, the thermal resistance should be minimized which implies minimum wall thickness. These conflicting requirements plus the thermal expansion compatibility between the heat sink and the device to be cooled are discussed in the context of available materials, applied to an IGBT module.

II. APPLICATION TO IGBT

Consider an IGBT module consisting of four Infineon Technologies (Siemens) SIGC05T60SNC IGBT dies, 2.29-mm square, applied to a 1-cm^2 microchannel heat sink. The IGBT specifications for pulsed mode operation imply power dissipation of 1,180 W/cm^2 over the active region with the duty ratio limited by a maximum junction temperature of 150 C.

A. Die Thermal Resistance and Compatibility

The approximate thickness and thermal conductivity, k, of the die layers and bond layer appear in Fig 1. The thermal resistance for each planar layer is $R = \Delta x/kA = \Delta T/P$, where Δx is layer thickness and ΔT is temperature difference. The dominant thermal resistance of the die is the SiO_2 insulating layer. The total thermal resistance, R_{total} , which is the sum of the thermal resistances for all the layers, implies a temperature difference across the IGBTs of 41.7 C for an applied power flux of 1,180 W/cm^2. The IGBT die can be bonded to the heat exchanger with a low-lead solder such as Castin. This implies a temperature drop of 7.2 C across the bond layer. The total temperature

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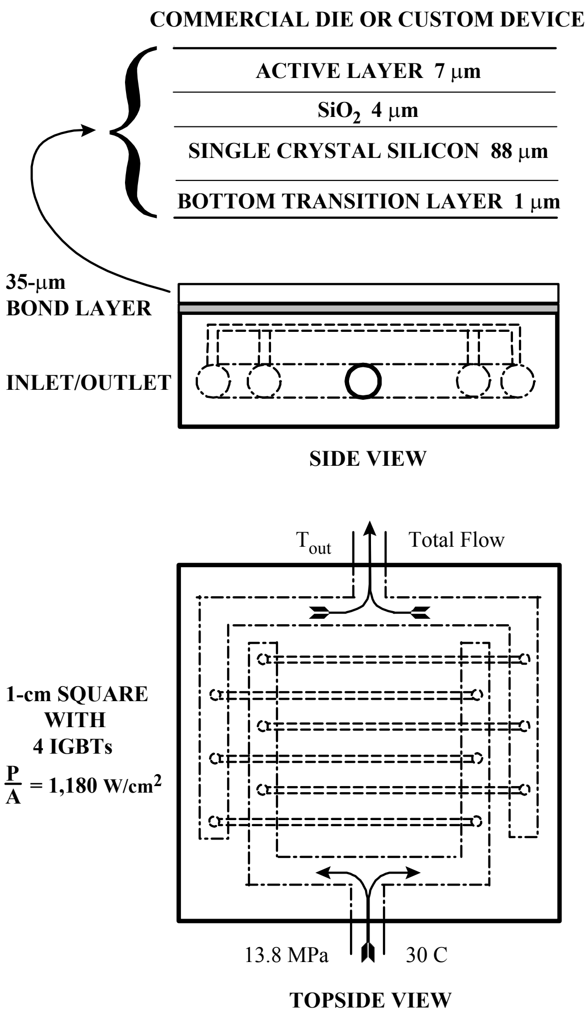


THERMAL CONDUCTIVITY	THERMAL RESISTANCE
k_{active} = 150 W/m-K	R_{active} = 0.0004667 K/W
k_{SiO_2} = 1.38 W/m-K	R_{SiO_2} = 0.0289900 K/W
k_{Si} = 150 W/m-K	R_{Si} = 0.0058670 K/W
k_{bottom} = 150 W/m-K	R_{bottom} = 0.0000667 K/W
	R_{device} = 0.0353904 K/W
k_{bond} = 57 W/m-K	**R_{bond} = 0.0061403 K/W**

HEAT-SINK SPECIFICATIONS

L = 10,000 μm r = 25 μm p = 13.8 MPa T_{inlet} = 30 C

Cu alloy z = 67 μm w = 42 μm s = 92 μm N_{pipes} = 108
k = 189 W/m-K h_c = 460 kW/m^2-K Y = 83 MPa
T_{out} = 65.1 C Total Flow = 9.18 g_{H_2O}/s

Invar 42 z = 37 μm w = 12 μm s = 62 μm N_{pipes} = 160
k = 10.7 W/m-K h_c = 326 kW/m^2-K Y = 295 MPa
T_{out} = 55.1 C Total Flow = 13.5 g_{H_2O}/s

THERMAL RESISTANCES PER PIPE

Cu alloy R_{pipe} = 0.340 K/W R_{conv} = 1.384 K/W
Invar 42 R_{pipe} = 4.194 K/W R_{conv} = 1.953 K/W

PARALLEL THERMAL RESISTANCES

$$R_{sink} = (R_{pipe} + R_{conv})/N_{pipes}$$

HEAT SINK TOTAL THERMAL RESISTANCE

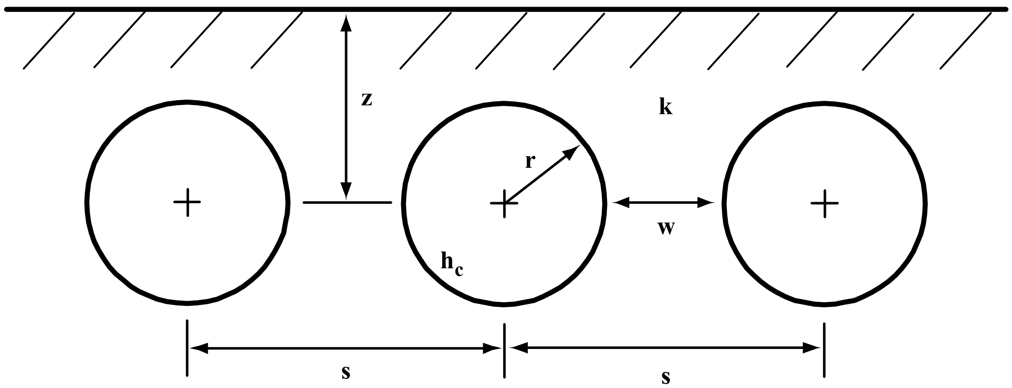
$R_{Cu\ alloy}$ = 0.01596 K/W **$R_{Invar\ 42}$ = 0.03841 K/W**

Figure 1. Semiconductor device and counterflow microchannel heat exchanger.

difference from the IGBT active region to the thin upper surface of the heat exchanger is 49.0 C.

The geometry and formulas[6] in Fig 2 quantify the pipe array and thermal design. The mechanical constraints of thermal expansion compatibility and mechanical integrity due to high pressure in the microchannels drive the selection of heat-sink materials. The thermal expansion coefficient of a single-crystal-silicon substrate is α_{Si} = 2.33 μm/m-K, whereas that of pure copper is α_{Cu} = 17.6 μm/m-K at 400 K. If both the die and the copper are heated to the maximum die temperature for bonding, then as both cool together the die will be placed under compression by the underlying copper that contracts more rapidly[7]. Gillot *et la*[2] brazed their IGBTs to copper and did not report any thermal expansion failures.

A candidate material should have high yield strength, Y, to minimize wall thickness between microchannels; a high thermal conductivity, k, to reduce thermal resistance; and a good match to the thermal expansion coefficient of silicon to minimize tensile loading. Commercial bronze[8] copper alloy (90Cu-10Zn) has Y = 83 MPa, k = 189 W/m-K, and $\alpha_{Cu\ alloy}$ = 18.4 μm/m-K. The yield strength is approximately 2.5 times that of copper but the thermal conductivity is lower by 50%. For a thin delicate substrate that may fracture, Invar 42[8] (42Ni-58Fe) with $\alpha_{Invar\ 42}$ = 4.9 μm/m-K, k = 10.7 W/m-K, and Y = 295 MPa could be used. The thermal expansion coefficient for Invar 42 provides a good match to silicon and would reduce the compressional loading



$$R_{pipe} = \frac{1}{2\pi k L} \, ln \left[\frac{s}{\pi r} \sinh\left(\frac{2\pi z}{s}\right) \right] \text{ PER PIPE} \qquad R_{conv} = \frac{1}{2\pi r L h_c} \text{ PER PIPE}$$

L = PIPE LENGTH, k = THERMAL CONDUCTIVITY, h_c = CONVECTIVE HEAT-TRANSFER COEFFICIENT

Figure 2. Thermal resistance from an array of pipes to the surface of a semi-infinite medium.

on the substrate by approximately 80%. There are other low expansion alloys[7] that closely match the expansion coefficient of silicon, but the exact coefficient depends critically on the material composition, cold working, plus the thermal history which includs the bonding process.

B. Heat-Sink Design

A counterflow design is adopted that involves a fluid manifold system that moves fluid in opposite directions in adjacent pipes. The 1-cm square counterflow design, shown in Fig. 2, minimizes temperature gradients across the heat sink and produces uniform tensile loading on the wall between pipes.

The wall thickness, w, is approximated using the hoop stress formula for a long cylinder[9], $S_{hoop} = pr/w$, where r = 25 µm is the microchannel radius, and p = 13.8 MPa = 2,000 psi is the inlet pressure. For commercial bronze and a safety factor of 10, the wall thickness is 42 µm. This implies 108 microchannels on a center-to-center spacing, s, of 92 µm at a depth, z, of 67 µm. The heat sink thermal resistance per pipe, R_{pipe}, is 0.340 K/W. For Invar 42 and a safety factor of 10, the wall thickness is 12 µm, there are 160 microchannels on a center-to-center spacing of 62 µm at a depth of 37 µm, and the thermal resistance per pipe is 4.194 K/W.

Fluid flow in a 50-µm diameter duct with an inlet pressure and temperature of 2,000 psi and 30 C was modeled with a computer code for water[5]. For a Cu alloy heat exchanger that dissipates 11 W/pipe plus 1.2 W due to fluid friction, the flow is 85 mg/s per pipe, the exit fluid temperature is 65.1 C, and the average value of h_c is 460 kW/m^2-K. The thermal resistance of a pipe for convective heat transfer from the heat sink wall to the fluid, R_{conv}, is 1.384 K/W.

The net thermal resistance per pipe is the sum of R_{pipe} and R_{conv}. Because there are 108 microchannels in parallel, the thermal resistance for the heat sink is that of a single microchannel divided by the number of microchannels, as noted in Fig. 1

For a Cu alloy heat sink the total thermal resistance is 0.01596 K/W. For 1,180 W/cm^2 dissipation, the average heat-sink fluid temperature is 47.5 C, and the fluid to bond-layer temperature difference is 18.8 C. The IGBT junction temperature and water flow are 115.3 C and 9.18 g/s (0.145 gal_{H2O}/min).

For an Invar 42 heat exchanger that dissipates 7.4 W/pipe plus 1.1 W due to fluid friction, the flow is 84 mg/s per pipe, the exit fluid temperature is 55.1 C, the average value of h_c is 326 W/m^2-K, and R_{conv} = 1.953 K/W. The heat sink thermal resistance is 0.03841 K/W, average heat-sink fluid temperature is 42.5 C, and the net temperature difference from the fluid to the bond layer is 45.3 C. The IGBT junction temperature is 136.8 C, and the net flow is 13.5 g/s (0.215 gal_{H2O}/min).

Although the junction temperature is less than the maximum junction temperature of 150 C, it is possible to reduce it further by adding antifreeze to the water and refrigerating to -20 C, a – 50 C reduction of inlet temperature. This will lower the active region for a Cu alloy heat sink to approximately 75 C and for an Invar 42 to approximately 95 C.

The heat sink examples using a Cu alloy and Invar 42 quantify performance for two materials with a similar mechanical design. The heat sink thermal resistance for Cu alloy is 31% of the total thermal resistance from fluid to active region with 80% of the heat-sink resistance due to convective heat transfer. A lower active region temperature could be achieved by doubling the pressure and halving the pipe diameter. This will roughly maintain the same convective rate, double the number of pipes, and halve the heat sink thermal resistance. Nickel 200[8] is an alternative to Invar 42 with a coefficient of expansion of 13.3 μm/m-K, a thermal conductivity of 70 W/m-K, and yield strength of 148 MPa. Nickel 200 has a better thermal expansion coefficient match to silicon than Cu alloy. The thermal conductivity is 6.5 times greater than Invar 42, the yield strength is 50% less, which implies a 17% reduction in the number of pipes to 134. The heat sink thermal resistance for Nickel 200 is half that for the Invar 42 example.

III. OTHER APPLICATIONS

The same methodology can be applied to many other dies and custom devices to enhance performance that is limited by heating of the active region. Applications to passive components include a high power compact film resistor, a high-power film capacitor, and the surface of a conductor subject to intense heating at a high repetition rate. Application to a ceramic dielectric or a ferrite material for a large high-energy component is possible in principle, but practical details such as operating a hydraulic system subject to continuous or pulsed voltages plus introduction of a microchannel impedance discontinuity in the media must be integrated into the overall design.

IV. SUMMARY

The design example of a liquid cooled IGBT module quantifies a 1,180 W/cm^2 microchannel heat sink cooling system that maintains the active region junction temperature below 115 C for a commercial bronze design and below 137 C for an Invar 42 design. Although the heat sink geometry and optimal heat-sink material has not been utilized, the design is within a small factor of the ultimate performance possible. Practical considerations such as fouling of the microchannels, thermal cycling, corrosion, and fabrication details have not been addressed but also influence the selection of materials. An improvement in performance is possible by reducing the die thickness and by minimizing the insulating-layer thickness of the electronic device. Application to a high-power electronic die, a film resistor, a film capacitor, and a current carrying conductor are straightforward.

V. DISCLAIMER

VI. REFERENCES

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