Cooling Microelectronics with Thermal Raceways

Chris G. Macris
Enerdyne Solutions, North Bend, WA 98045

Background

The heat generated by Integrated Circuit and discrete semiconductor chips has a damaging and limiting effect on performance. Thermal spreader technology allows a concentrated area of high heat to be distributed over a larger area, thereby reducing the average temperature of the chip.

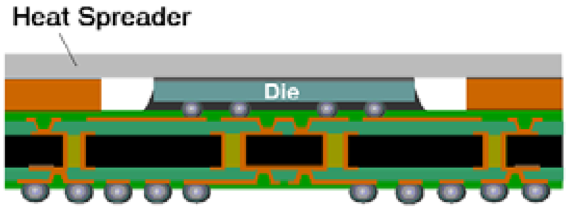


Figure 1

Heat spreaders are most efficient when heat is uniformly applied over the entire plate. However, heat spreaders with large contact areas are attached to heat sources with much smaller contact areas due to the further densification of electronic device packages. The result, a "spreading resistance," creates a higher local temperature at the location where the heat source is placed.

On a die level, heat sources can be a mix of multiple point regions, each with differing heat flux densities and corresponding temperatures. Therefore, while one area of the die may have a temperature well below the design point, another area of the die may exceed the maximum temperature at which the design will function reliably. Figure 2 is a temperature plot of a Pentium family processor.

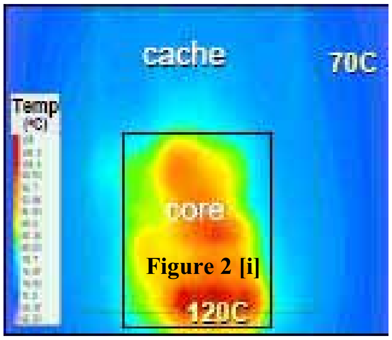


Figure 2 [i]

To satisfy the demands of these heat sources, heat spreaders must have high thermal performance and be directly attached to the active device in order to mitigate thermal interface resistance. Direct (eutectic) attachment requires the heat spreader to possess a coefficient of thermal expansion (CTE), which matches the die to avoid stress failure of the device.

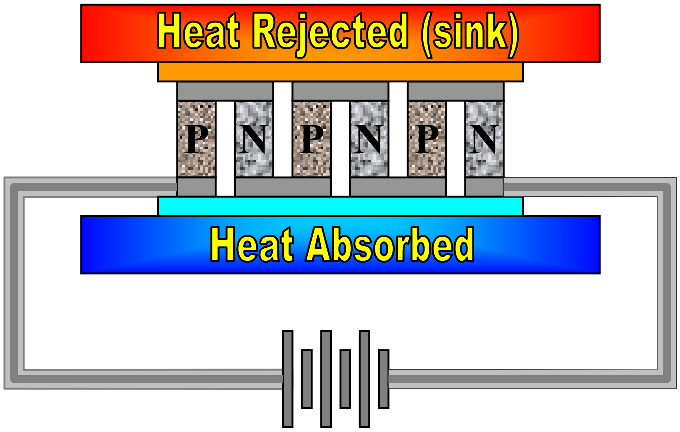
Typical metallic and diamond/carbon-based heat spreader materials have high thermal conductivities; however, the CTE values do not match active devices. CTE matching materials (metal matrix composites) provide marginal heat spreading performance.

Present Invention

Enerdyne's Polara™ technology combines passive thermal conduction and thermoelectric (Peltier) effects into a monolithic heat spreader device.

Peltier Effect

A current flowing through a circuit comprised of dissimilar conductors or semiconductors will cause an absorption (pumping) of heat energy at one junction and a liberation of the absorbed energy at another. Designed to cool below ambient temperature, conventional thermoelectric, or Peltier heat pumps are comprised of semiconductors of low thermal conductivity.



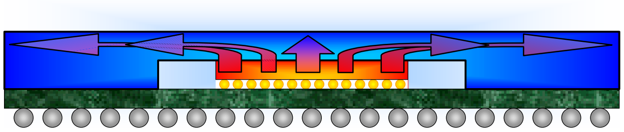
The heat removal rate/efficiency is determined by thermoelectric properties, joule losses, and passively conducted heat flowing counter to the direction of heat pumping:

$$Q_{couple} = \left[\left(\alpha_p + \alpha_n\right) TCI - I^2 R\right] - \frac{K\Delta TA}{HL}$$

Unlike conventional Peltier heat pumps, Polara™ was designed as a heat spreader: To operate efficiently at equal to or greater than ambient temperature. Therefore, materials were selected which possessed high thermoelectric properties and high thermal conductivities. The Heat removal rate/efficiency is determined by thermoelectric properties, joule losses, and passively conducted heat thermally in parallel with pumped heat:

$$Q_{couple} = \left[\left(\alpha_p + \alpha_n\right) TCI - I^2 R\right] + \frac{K\Delta TA}{HL}$$

Although monolithic in structure, Polara™ includes integrated thermocouples, which enable directional heat transfer with the application of current. These oriented thermocouples are “Thermal Raceways”, tailored features to preferentially and anisotropically pump heat away from point sources on a die. The use of Silicon and other matched CTE materials as Polara™ will allow for direct eutectic attach to active devices.



Analysis Methodology

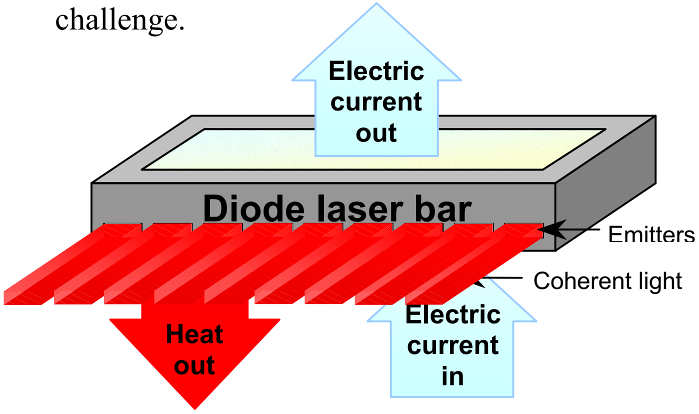
A computer based evaluation of this heat spreader technology was undertaken initially as a proof of principle; however, an additional benefit of this scientific approach is that significant trends and design guidelines have been readily obtained for ultimate reduction to physical practice.

The finite element model builder and numerical solver program "FlexPDE version 3" was utilized to model and generate all graphical results. "TNETFA", a thermal network program, provided corroborative data within an acceptable tolerance. Additionally, a benchmark simulation was run with ALGOR software and the results were found to agree with the FlexPDE data.

The models utilized identical device power source geometry and distribution, material thickness, heat spreader and heat sink geometry, sink interface material properties, convection coefficients and thermal conductivity values, judiciously selected from industry accepted sources.

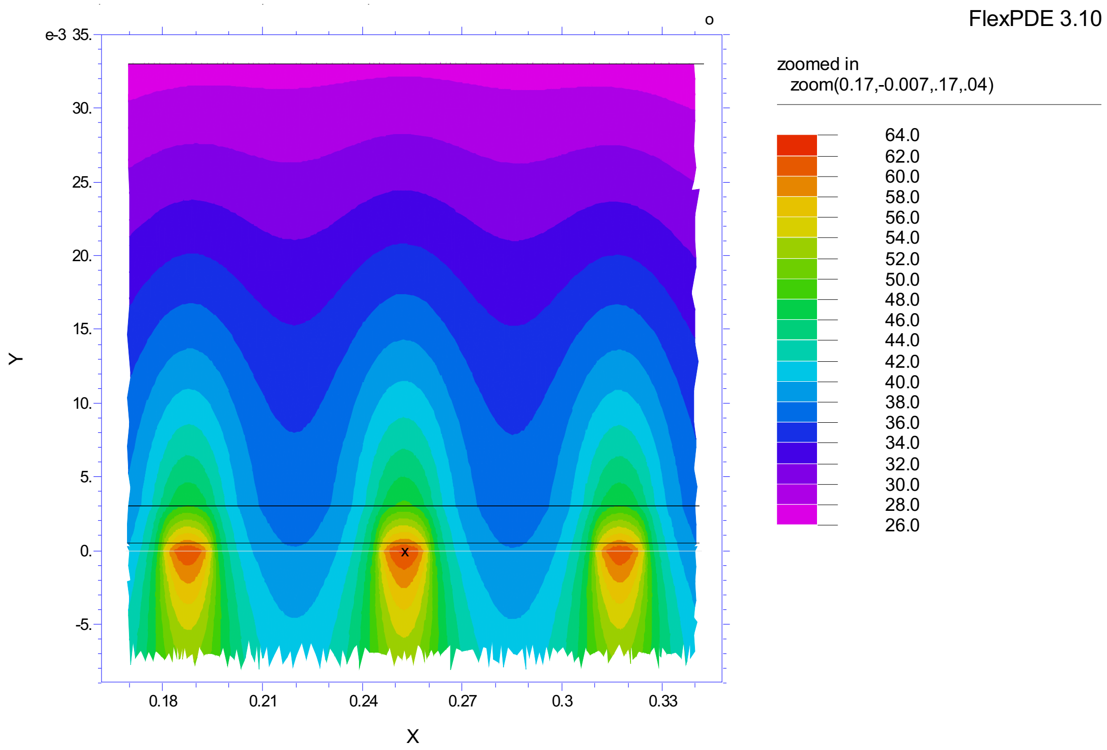
Case Example 1: Laser Diode Bar

High power laser diode bars consist of multiple heat sources (emitters) of uniform heat flux distributed on a common substrate. Emitter temperature clearly impacts optical power/efficiency and reliability. The relatively low thermal conductivity of GaAs, CTE matching issues, micron level emitter geometries and rising power dissipations add to the cooling challenge.

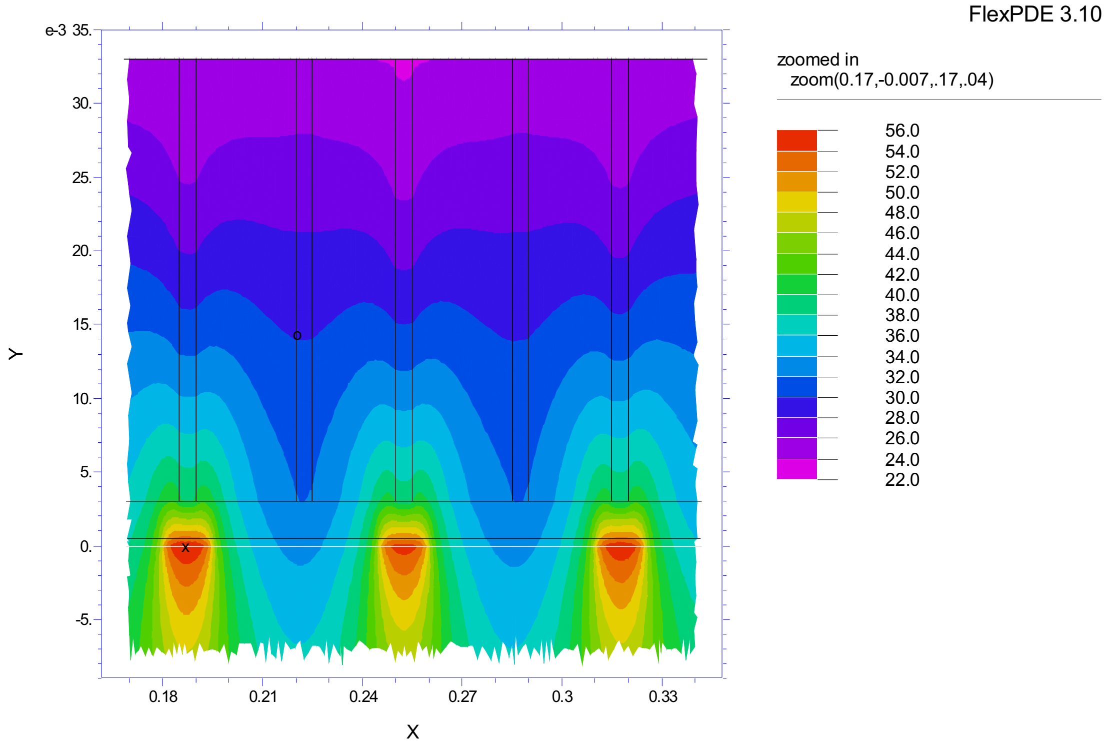


Simulation Variables

A GaAs-based diode bar was modeled with 19 emitters, each dissipating 2.63 watts and measuring 120um wide, 1um thick with 620um pitch. The simulation assumes all heat dissipation travels through the submount via a Au-Sn eutectic layer bonded to the P side.



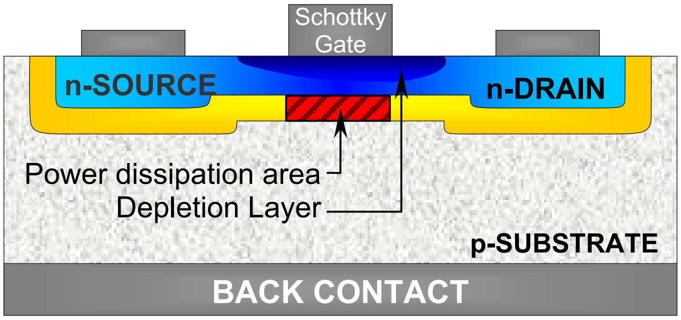
Laser bar, 2.63W emitters, facet view, P down; Grid#3 p2 Nodes=35410 Cells=17555 RMS Err= 9.3e-6



Laser bar, 2.63W emitters, facet view, P down, Polara; Grid#3 p2 Nodes=36100 Cells=17903 RMS Err= 1.e-5

Graphic Description

Graphic 1 is a sectional view (facet side) including 3 emitters and a Cu-Mo submount.
Graphic 2 is comprised of a Polara submount. The vertically oriented features denote junctions, heat absorbing immediately adjacent the emitters and heat rejecting junctions interstitially positioned.

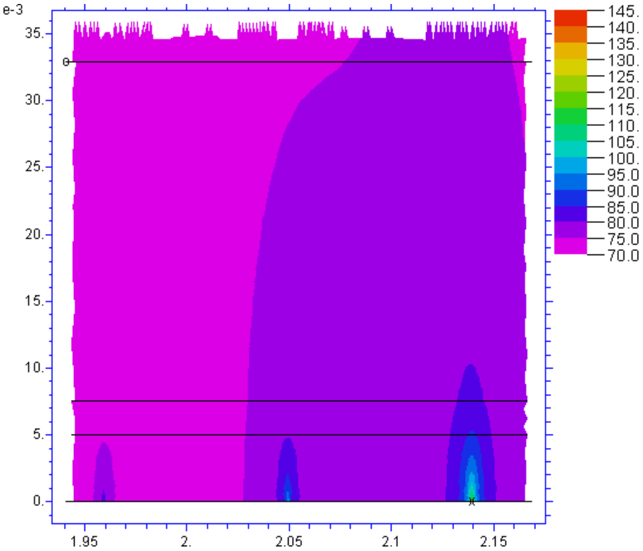


Case Example 2: GaAs MESFET Amplifier

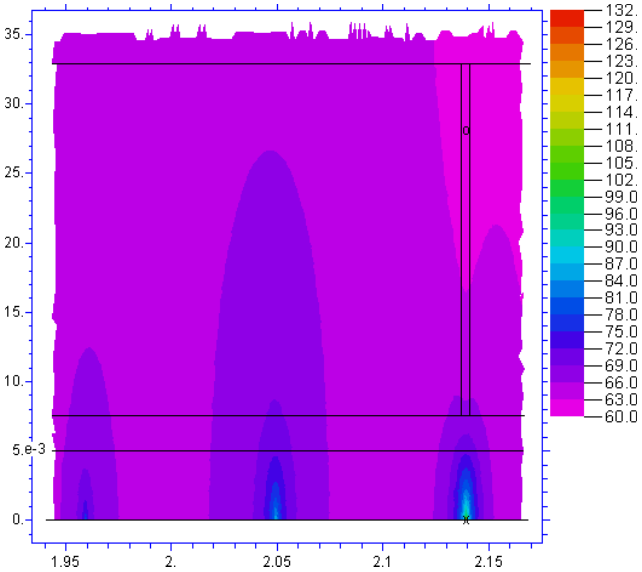
GaAs amplifiers consist of individual stages, each with multiple FETs positioned in parallel. With each successive amplification stage, power dissipation increases; therefore, the final stage becomes the peak operating temperature of the device. Similar to Case Example 1, the substrate material and heat source architecture and power levels require a eutectically bonded heat spreader/submount with good thermal properties.

Simulation Variables

A GaAs MESFET amplifier was modeled with 3 stages, each stage dissipating 2.40, 4.24 and 8.36 watts respectively. The simulation assumes all heat dissipation travels through heat spreader (including a raised pedestal feature) via a Au-Sn eutectic layer.



Graphic 3



Graphic 4

Graphic Description

Graphic 3 is a sectional view illustrating the 3 FET stages and a Cu-Mo heat spreader with integrated pedestal.

Graphic 4, is comprised of a Polara-based heat spreader. It was determined that all heat absorbing features be positioned immediately above the third stage for maximum gain. The heat rejecting junctions are positioned outside the field of view.

Conclusion

The results of the thermal simulations indicate significant point source temperature reductions are possible with focused heat absorption and vectorized transfer. Placement of the integrated heat absorbing and heat rejecting junctions is critical to performance as will be the alignment between Polara and active device.

Further study will include additional thermal modeling with specialized 3D packages such as Harvard Thermal's TAS software. Specific device specifications will be required from industry partners to increase model accuracy and applicability. In parallel with refined simulations, an empirical component will commence to address handling, bonding, power consumption concerns, grounding, and possible interference issues.

Terms

A = area of heat spreader/TEC (cm2)
L = thickness heat spreader/TEC (cm)
ρ = electrical resistivity (Ω-cm)
K = thermal conductivity (cal/sec/cm/°C)
ΔT = temperature differential (convert to Kelvin)
CTE = coefficient of thermal expansion (ppm/°C)
T = absolute temperature (Kelvin)
C = .24 (joules to calories conversion constant)
H = thermal spreading resistance
I = amperes
Qpassive = passive heat spreader heat transferred (cal/sec)
Qcouple = thermocouple heat transferred (cal/sec)
R = electrical resistance (ohms)
I^2R = convert to calories/sec.
α_n = Seebeck coefficient (N-type, microvolts/°C)
α_p = Seebeck coefficient (P-type, microvolts/°C)

Founded in 1998, Washington-based Enerdyne Solutions LLC is engaged in the research, development, manufacturing, and licensing of advanced thermal management technology with an emphasis on higher performance, lower cost, and reduced form-factor. The Company's leading Polara™ line of heat spreaders provides ambient cooling. of many devices of high heat flux density, including computer chips, lasers, and RF amplifiers. Other proprietary and patented products include the high-performance PermaFrost™ thermoelectric heaters/coolers and ThermPower™ electrical generators.

For more information contact:
Chris Leyerle, Enerdyne Solutions
P.O. Box 2660
North Bend, WA. 98045

Telephone: 425-888-1880
Email: leyerle@enerdynesolutions.com.