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DESIGN AND TESTING OF A CARBON FOAM BASED SUPERCOOLER FOR HIGH HEAT FLUX COOLING IN OPTOELECTRONIC PACKAGES

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ABSTRACT

The feasibility of using carbon foam as a heat sink and heat spreader in optoelectronic packages is assessed. A "supercooler" is designed, fabricated and tested to verify its cooling capability under high heat flux conditions in a typical optoelectronic package. The supercooler uses carbon foam as a primary heat transfer material. Water is soaked into the carbon foam and under evacuated pressure, boiling is initiated under the heating region to provide enhanced cooling.

Experiments were conducted for a heat flux of up to 400 W/cm^2 deposited over a heating area of 0.5 mm x 5 mm. Two dimensional transient temperature distributions were recorded using a high speed infrared camera. Data were obtained for steady heating, as well as periodic heating with frequency up to 8 hz. Results show that the supercooler is very efficient in dissipating heat away from the heating region. Data obtained under 8 hz periodic heating with a peak power input of 10W, for example, showed that the temperature of the heated surface rises quickly to a local maximum of 15 to 20 °K above the ambient. The heated surface is then cooled uniformly back to a near ambient condition (with a maximum temperature of less than 5 °K above ambient) during the cooling half of the cycle (less than 0.0625 sec after the heating is turned off). The average cooling rate during the cooling period exceeds 170 °K/s.

A numerical model, based on COMSOL, is developed to interpret the experimental data and to provide insights on the relevant physics responsible for the rapid cooling. Numerical data are presented to demonstrate how the supercooler can be further improved and adopted for other applications.

Key words: high heat flux, cooling, carbon foam, supercooler

INTRODUCTION

With the increased interest and advances in the design of optoelectronic devices [1] and the increase in the power level of lasers utilized in many future space-based communication applications, there is an increasing need for the development of an effective thermal management strategy to maintain temperature uniformity over surfaces at which miniature optical devices (with length scale of mm or less) are mounted in order to preserve optical alignment. The strategy must account for not only the dissipation of the high density power generation (up to 400 W/cm^2), but also the prevention of large temperature gradient on the device surface during rapid transient heating, with typical time scales as short as a few micro-seconds. Effective thermal spreading, as well as heat dissipation, are important challenges which must be met by modern optoelectronic packages.

The objective of the work is to demonstrate the effectiveness of non-metallic foam as a heat spreader, liquid wick and heat sink material for electronic package with localized high heat flux. In recent years, there has been a growing interest in using high-thermal-conductivity foam material for heat transfer applications [2-5]. For both single-phase [2] and multi-phase flows [3-5], high-thermal-conductivity foams were demonstrated to be effective in providing heat transfer enhancement. For example, using graphite foam as an evaporator soldering directly to the back of a silicon CMOS die in a thermosyphon [4], a cooling heat flux of 150 W/cm^2 was reported with the chip temperature maintained at less than 71 °F. Since high-thermal-conductivity non-metallic foams have many properties which are favorable for thermal management purposes (e.g. thermally stable, low in weight and density, chemically pure, low thermal expansion, resist thermal stress and shock, and

inexpensive), additional studies to understand the heat transfer mechanisms and to determine the feasibility of using these materials for the cooling of optoelectronic packages with localized high heat flux are warranted.

Based on the geometry and heating requirement of a prototype package under consideration by an optoelectronic research group at UCSB, a carbon foam based "supercooler" is fabricated and its heat transfer performance is characterized experimentally. This paper summarizes result of the experimental and modeling efforts.

DESIGN OF THE "SUPERCOOLER"

The specific optoelectronic package used as a basis of the design of the supercooler is shown in Figure 1. As shown in the figure, the dimension of the heating area is small (5.8 mm by 0.5 mm). The active material (InGaAsP and InP) is soldered to an AlN substrate which acts as a thermal spreader. The package is then soldered to kovar which is attached to a TE cooler for thermal control. The utilization of kovar (which has a small coefficient of thermal expansion) is generally considered to be necessary to maintain the necessary optical alignment of the different components of the package.
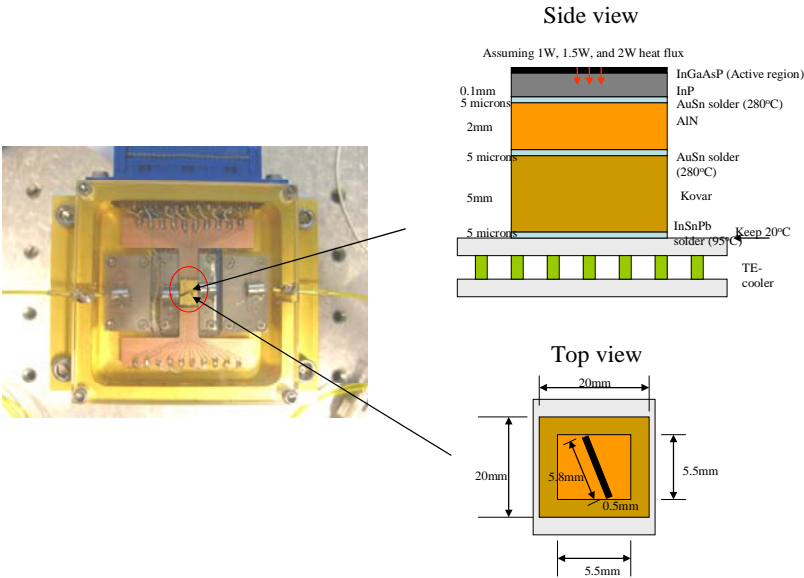

Figure 1: The prototype electronic package under consideration for cooling by the supercooler.

The "supercooler" designed specifically to meet the thermal requirement of the package is shown in Figure 2. The heating area is simulated by depositing a thin resistive layer (with a dimension of 0.5 mm by 5 mm) on an AlN substrate. In contrast to the actual package, the AlN substrate is brazed to a kovar slab only along its perimeter (approximately 1mm width). The interior of the substrate is brazed to a carbon foam tip. The carbon foam tip is a part of a carbon foam cylindrical shell which is soaked with liquid water to allow for both high heat transfer and thermal diffusion within the solid carbon matrix and two-phase boiling heat transfer in the porous region. The carbon foam shell is brazed to a copper cylindrical shell which provides the outside mechanical support and heat dissipating area for the supercooler.
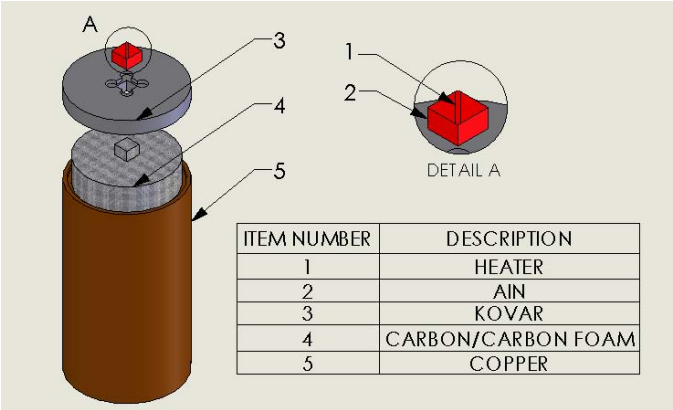

ITEM NUMBER	DESCRIPTION
1	HEATER
2	AlN
3	KOVAR
4	CARBON/CARBON FOAM
5	COPPER

Figure 2: Schematic of the supercooler.

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An interior view of the supercooler and the relevant geometric dimensions are shown in Figure 3. The size of the copper cylinder is chosen so that there is sufficient area to dissipate the expected power input (1 to 10 W) by natural convection. The thickness of the carbon foam is selected largely based on practical constraints (the dimension of carbon foam available commercially and the brazing process). Prior to the experiment, the supercooler is sealed and evacuated down to 10^{-6} Torr. A small amount of three-time de-ionized and de-gas water (20 gm) is then injected into the carbon foam shell to act as a two-phase coolant within the carbon foam.

PART NUMBER	DESCRIPTION
1	HEATER and AIN
2	KOVAR
3	CARBON/CARBON FOAM
4	COPPER
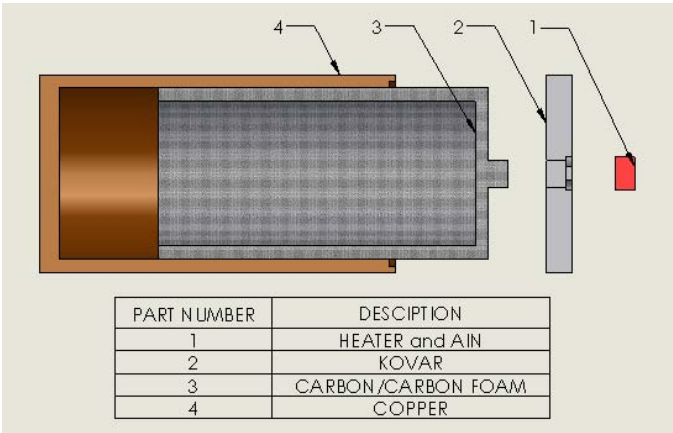
Copper Cover Dimension
D = 3 cm, L = 5.4 cm

Thickness of Carbon Foam Shell
d = 0.4 cm

Figure 3: Interior view of the supercooler and the relevant geometric dimensions.

EXPERIMENT

The experimental set up is shown in Figure 4a. A high speed (1680 hz) infrared camera (SBF-180) is the primary temperature measurement equipment used in the experiment. To eliminate any uncertainty due to the effect of surface emissivity, the top of the supercooler, including the heating area, is coated with black paint. The experimental setup, with the heating surface of the supercooler facing upward, together with the camera are shown in Figure 4b. Data were also obtained with the heating surface facing downward to assess the effect of gravity-driven buoyancy on the performance of the supercooler. All tests were conducted with no active cooling on the outside of the supercooler.
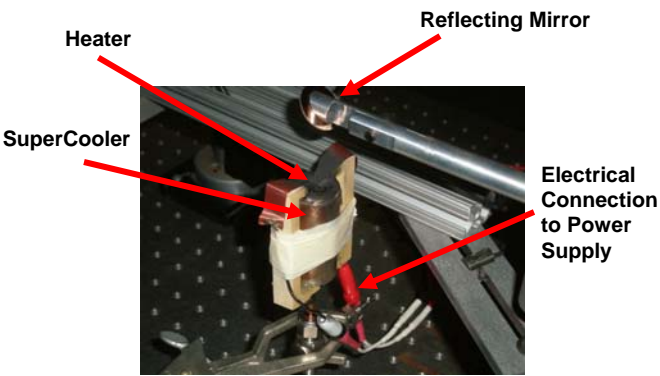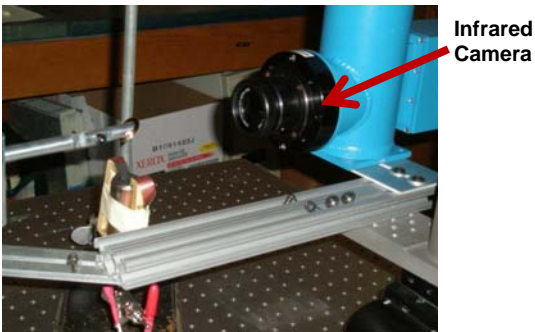

Figure 4a: Top view of the experimental setup.

Figure 4b: Experimental setup, together with the infrared camera used in the temperature measurement.

Steady Heating

The maximum temperature observed at the heating surface under a steady power input of 4 W and 10 W are shown in Figures 5a and 5b. At the initial stage of testing, there was a concern about securing good electrical contact to the thin resistive layer. A masking tape was wrapped around the mechanical contact on the side of the supercooler to ensure good electrical connection as shown in Figure 4a. This leads to additional thermal insulation and a slight increase in the maximum temperature as shown in Figure 5a. Subsequently, it was determined that good electrical contact was secured and all the remaining tests were conducted without the masking tape.

Data from the steady heating case show readily the high heat transfer capability of the supercooler. Based on the maximum temperature observed and using the area of the heating element, the average heat transfer coefficient for the 4-W and 10-W case are approximately 160 W/(m^2-K) and 100 W/(m^2-K) respectively. The effect of the heater orientation is shown in Figure 5b for the 10-Watt case. In general, the effect of the heater

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orientation appears to be insignificant. The slight variation in the maximum temperature can probably attributed to experimental uncertainty (e.g. variation in setup, power input, ambient conditions, etc.).
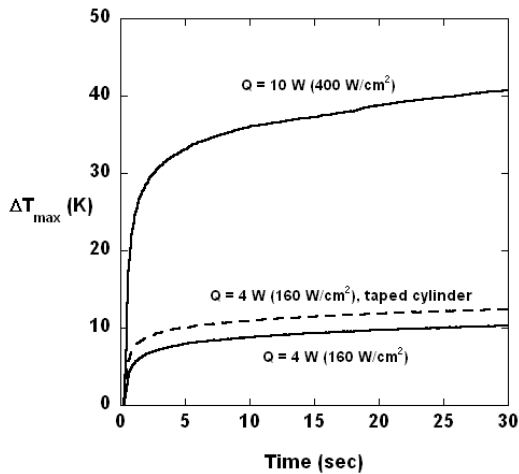

Figure 5a: Effect of heating power for steady heating tests.

Even for the steady heating case, the supercooler showed a remarkable cooling capability as the temperature of the surface drops rapidly (in less than 1 sec.) after the power is turned off (see the 10 W case as shown in Figure 5b). This result demonstrates that the supercooler with carbon foam can lead to not only a high heat transfer coefficient, it is also a thermal diffuser which can diffuse heat quickly away from the high temperature region when the heating is turned off.
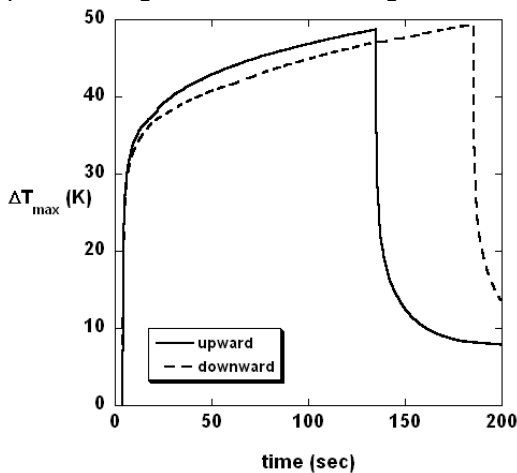

Figure 5b: Effect of heater orientation for the steady heating test with 10 W.

Periodic Heating

In view of the rapid temperature reduction and heat dissipation observed in the steady heating tests, a series of tests were conducted to demonstrate the heat transfer behavior of the supercooler under the condition of a periodic heating input. Tests were conducted with a regular square-wave heating input (i.e. the power-on period equal to the power-off period) with a peak power of 5W and 10W with different frequencies (0.5 hz, 1 hz, 2 hz, 4 hz and 8 hz).

The maximum temperature rise for the 5W-4hz and 10W-8hz runs are shown together with the input power transient in Figures 6a and 6b. The 2D infrared image of the top surface for the third and fourth heating cycle of the 10W-8hz case, together with the corresponding image for the 10W steady heating case, are shown in Figure 7. It can be readily observed that the supercooler
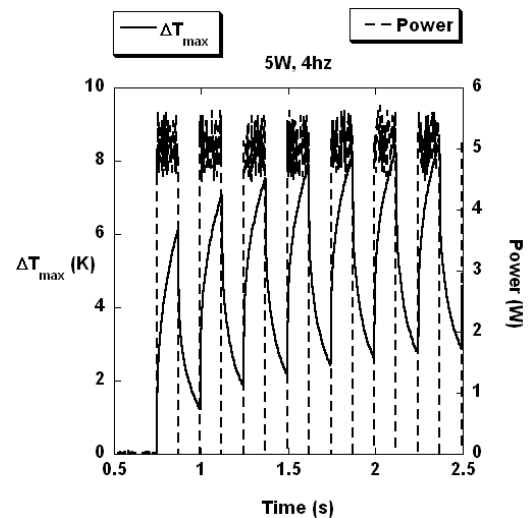

Figure 6a: The input power transient, together with corresponding maximum temperature transient, for the 5W-4hz run.
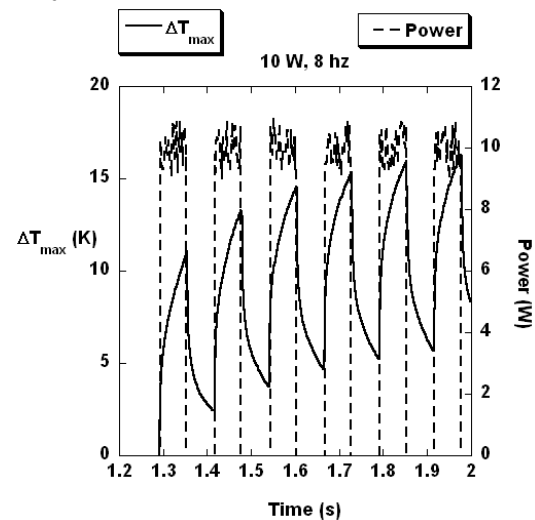

Figure 6b: The input power transient, together with corresponding maximum temperature rise transient, for the 10W-8hz run.

showed a remarkable ability to dissipate heat, as the maximum temperature drop almost instantaneously as the power is turned off.   The rapid cooling effect is also felt uniformly across the whole top surface, away from the heating area, as shown by the two-dimensional infrared images shown in Figure 7.

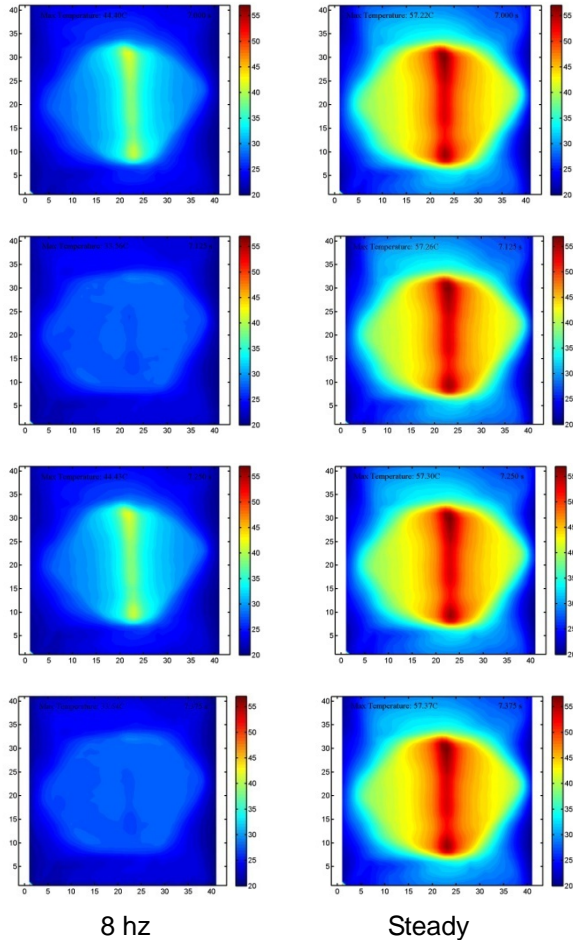|	
8 hz	Steady

Figure 7: The 2D infrared image of the heating surface for the third and fourth heating cycle of the 10W-8hz run, together with the corresponding image for the 10W steady heating case. (The range of the temperature scale in these figures is 20 °C to 55 °C)

The maximum temperature rise for the 5W and 10W runs with different frequency, together with the corresponding steady heating run, are shown in Figures 8 and 9.   For each of the periodic heating case, the maximum temperature oscillates with the same frequency as the input power between an upper and lower bound, while the overall average temperature increases with time.
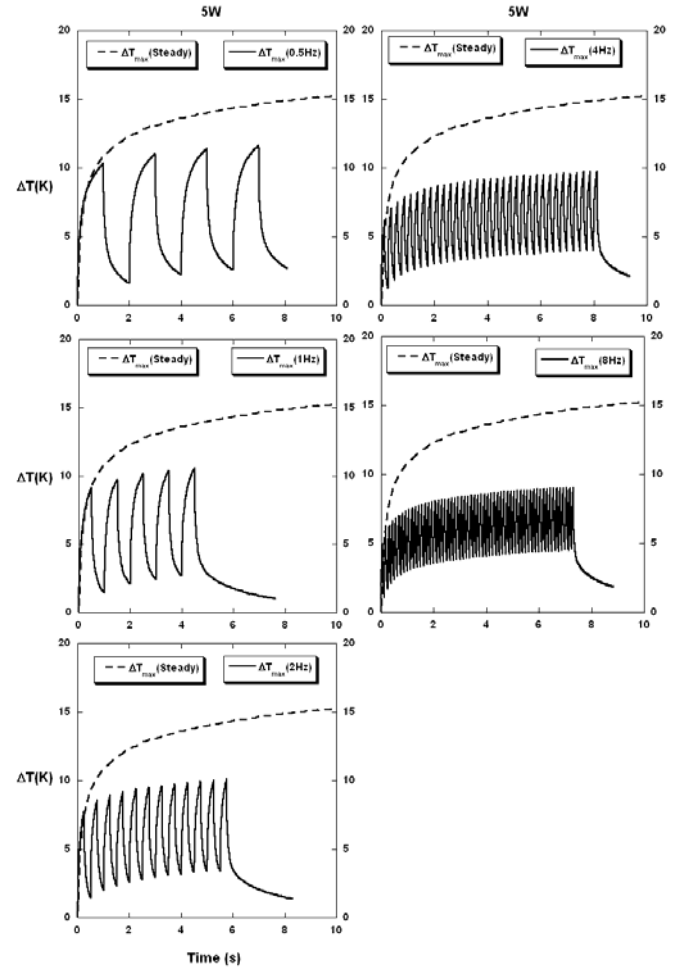

Figure 8: Maximum temperature rise for the 5W periodic heating runs with different frequency, in comparison with the 5W steady heating run.

Plots of these upper and lower bounds at the different frequency for the two cases are shown in Figures 10a and 11a. Based on the reduction of the maximum temperature during the off-period of the power input cycle, average cooling rates (in °K/s) for each cycle are estimated and shown in Figures 10b and 11b. It can be readily observed that the average cooling rate increases with increasing power and frequency, with a maximum rate of about 170 °K/s. Physically, the heating characteristic of the supercooler under oscillatory heating is expected to approach the steady heating case in the limit of high frequency, when the characteristic time of cooling is much shorter than the period of oscillation.   This result therefore suggests that the characteristic cooling rate of the supercooler is larger than 170 °K/s with a cooling time constant of less than 0.0625 sec. (half of the period of an 8 hz oscillation).
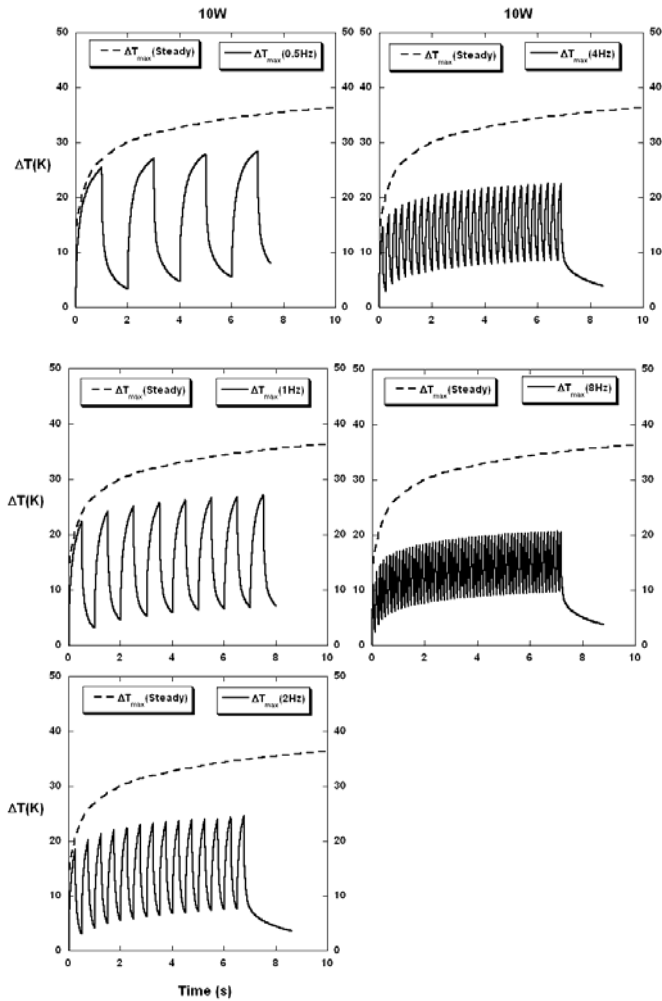
Figure 9: Maximum temperature rise for the 10W periodic heating runs with different frequency, in comparison with the 5W steady heating run.
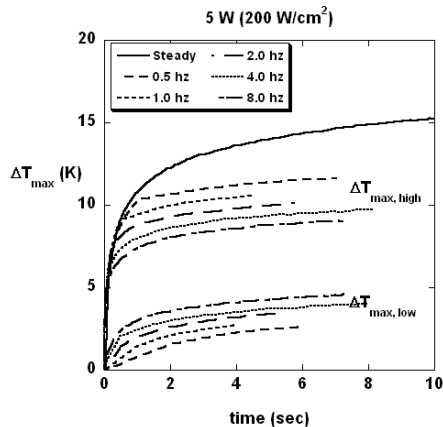

Figure 10a: The upper and lower bound of the maximum temperature rise for the 5W periodic heating runs with different frequency, in comparison with the 5W steady heating run.
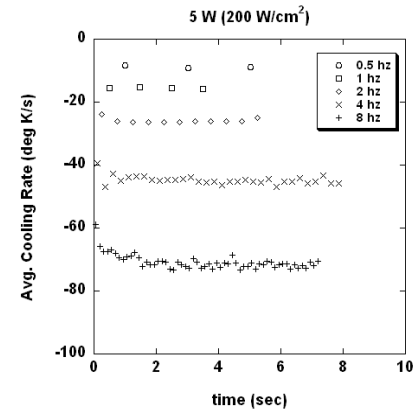

Figure 10b: The average cooling rate for the 5W periodic heating runs with different frequency, in comparison with the 5W steady heating run.
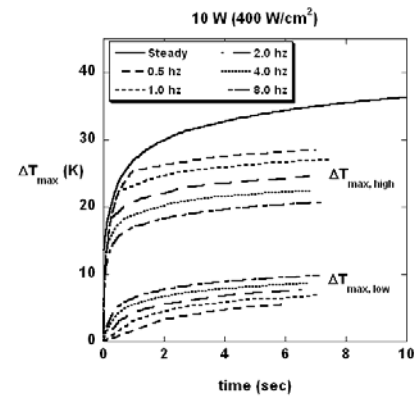

Figure 11a: The upper and lower bound of the maximum temperature rise for the 10W periodic heating runs with different frequency, in comparison with the 10W steady heating run.
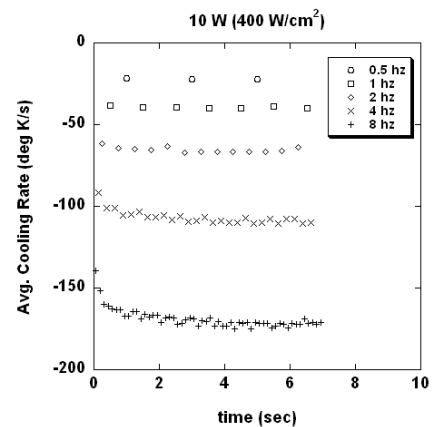

Figure 11b: The average cooling rate for the 10W periodic heating runs with different frequency, in comparison with the 10W steady heating run.

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Data in Figures 10a and 11a also show that as the frequency of the heating input increases, the maximum temperature oscillates with a narrower bound and a lower average temperature. The range of temperature is much lower than the corresponding maximum temperature rise for the steady heating case. For example, at 7 seconds after the initial heating for the 10W-8hz case, the upper and lower bound of the maximum temperature oscillation are at 20 and 10 °K above the ambient temperature respectively, while the maximum temperature for the 10W steady heating case is at 35 °K above ambient. Again, this lower average temperature can be attributed physically to the fact that the characteristic cooling time of the supercooler is less than 0.0625 sec. This result suggests that for thermal packages operating under a condition of highly localized periodic heating, the characteristic cooling time of the package should be included as one of the important design parameters in the assessment of a specific design.

ANALYSIS

A thermal model of the supercooler is constructed using COMSOL to understand the controlling physics of the heat transfer processes. A schematic of the model is shown in Figure 12. For simplicity and to focus the modeling effort on the initial heating period, the current model simulates only the top part of the supercooler accounting for the carbon foam, kovar and AlN structural design. "Contact resistance" is included in the model to account for the the effect of joining (or brazing) different materials into one unit. The effect of the carbon foam and copper cylindrical shell will be important in the "long-time" thermal behavior of the supercooler. This effect will be considered in the future. The current model also does not include the presence of liquid water in the carbon foam. The mechanism of two-phase flow and boiling in carbon foam is currently not well understood. Convective heat transfer and boiling/condensation within the foam is thus not included in this model. An effective heat transfer coefficient at the bottom surface of the carbon foam (h_b) and an effective heat transfer coefficient at the top surface of the AlN surface (h_t) are used to account for the overall heat dissipation from the supercooler. Due to this simplification, the model is not expected to be able to simulate quantitatively all of the observed heat transfer behavior of the supercooler, particularly in cases with periodic heating. The model is thus intended only to provide some qualitative assessment of the heat transfer characteristics of the supercooler.

The 4-W steady heating case is the basis of the analytical study. Numerical experiments show that a relatively high heat transfer coefficient both at the surface of the AlN and at the bottom of the carbon foam

base are needed to correlate the measured temperature rise. The predicted maximum temperature increase for different values of the top heat transfer coefficient h_t with a bottom heat transfer coefficient $h_b = 1000$ W/m^2-K and different top heat transfer coefficient h_t are compared with the measured data and shown in Figure 13. A top heat transfer of $h_t = 2000$ W/m^2-K appears to "fit" the measured maximum temperature increase effectively. When the power is turned off at 30 sec., the model also predicts accurately the rapid temperature reduction observed. The measured temperature distributions obtained by the infrared camera during the heating transient are compared with the COMSOL prediction in Figure 14. The model is quite effective in capturing the highly localized heating behavior around the heating region.
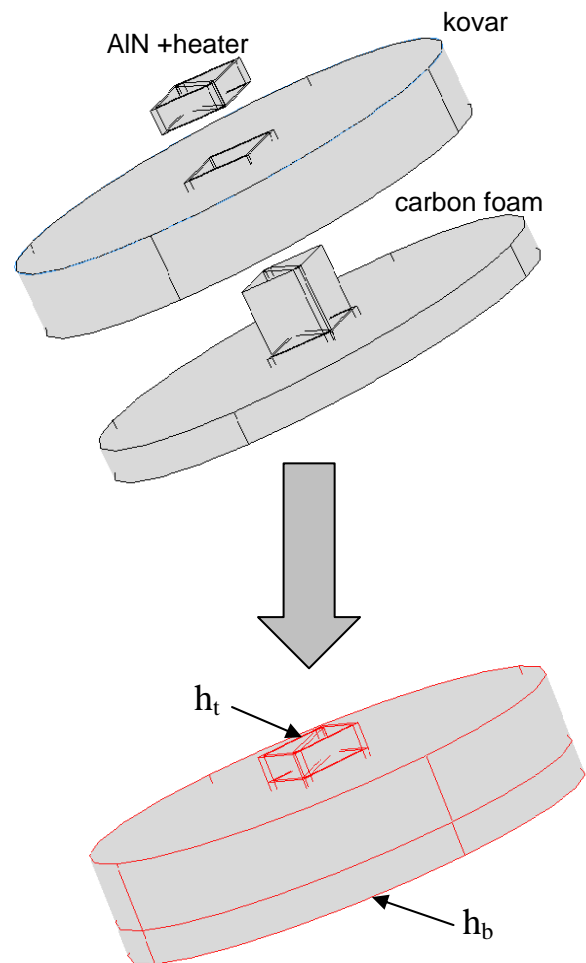

Figure 12: Schematic of the supercooler geometry and the convective heat transfer boundary conditions modeled by COMSOL.

The relatively high value of the top and bottom heat transfer coefficient (e.g. the typical heat transfer coefficient in air is in the range of 10-100 W/m^2-K) needed to correlate the experimental data show that the low pressure boiling within the supercooler has a definite role in the cooling process observed. This boiling mechanism, together with the wicking of liquid into the heated region, need to be understood in the future design and improvement of the supercooler.
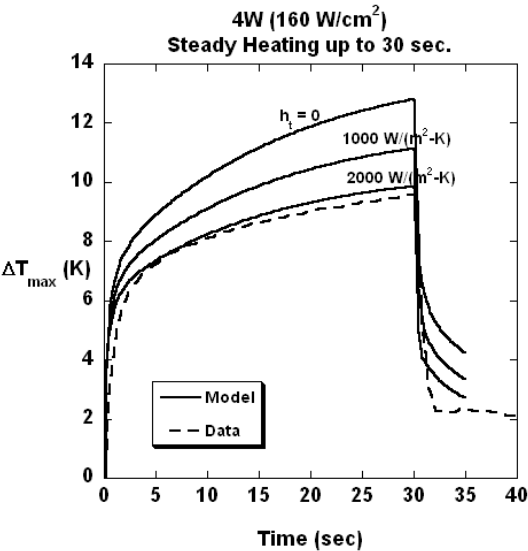

Figure 13: Comparison between the COMSOL prediction of the maximum temperature increase and experiment for different values of the top heat transfer coefficient (h_t) with a bottom heat transfer coefficient (h_b) of 1000 W/(m^2-K)

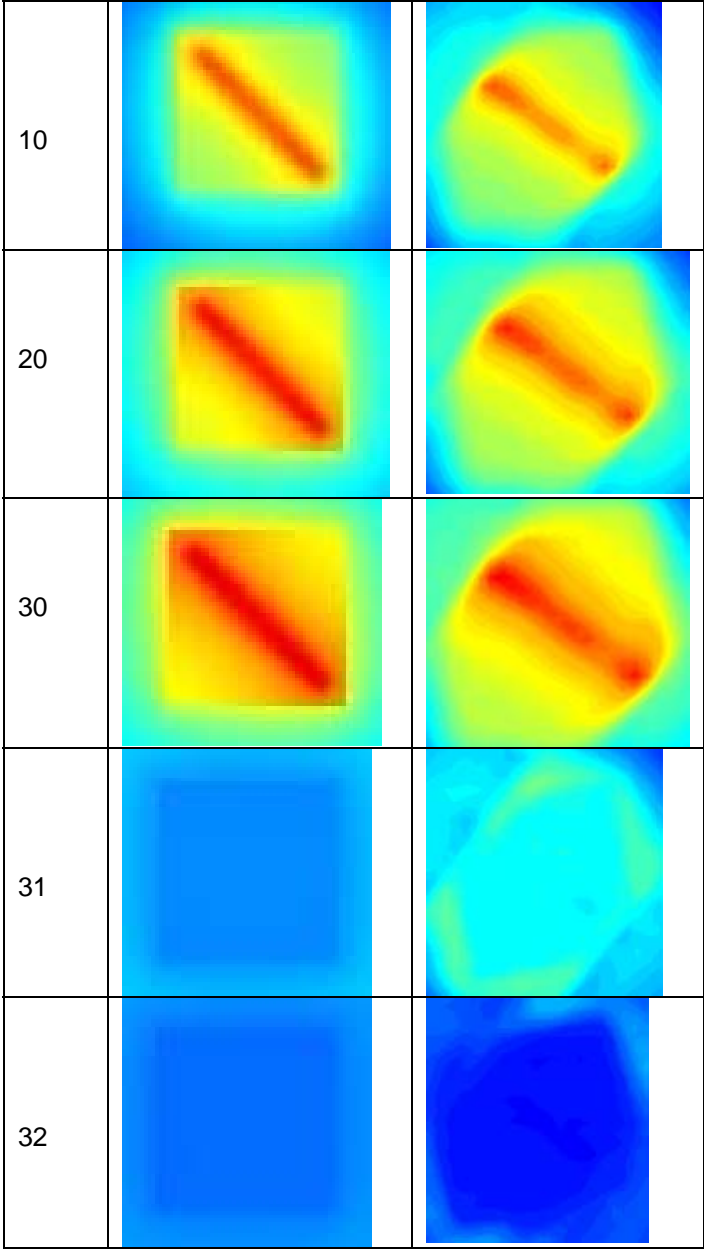| Time (sec.)	Model (COMSOL)	Infrared Image
1.0		
5.0		

Figure 14: Comparison between two-dimensonal temperature distribution around the heater at different time as predicted by COMSOL (left) and measurement by the infrared camera (right)

CONCLUSION

A supercooler is fabricated using carbon foam as the primary heat transfer material for cooling.   The carbon foam is soaked with water and the supercooler is operated under evacuated low pressure to ensure that two-phase boiling is occurring to enhance heat transfer. The specific design is directed toward the cooling of a prototypical optoelectronic package in which heat is

generated in the order of 1 to 10 W over a region with dimension of 0.5 mm x 5 mm. The corresponding heat fluxes are 40 and 400 W/cm^2.

Results show that carbon foam and the supercooler are effective in providing high heat transfer rate at the heating surface. Under a constant heating power input, the maximum temperature rise was maintained at a moderate level (40 °C after 30 sec. of heating with a power input of 10 W). The supercooler shows a remarkable capability to dissipate heat quickly and efficiently away from the heating area. Under periodic heating up to 8 hz, the cooling rate was observed to exceed 170 °K/s.

A numerical model of the supercooler, excluding the two-phase boiling/condensation effect, is developed using COMSOL. The model is effective in correlating the observed data. However, high heat transfer coefficients are required to obtain agreement with the measured data. An accurate understanding of the two phase flow boiling/condensation process occurring within the carbon foam is clearly needed to to further improve the performance of the supercooler and to adapt the technology to other high heat flux heating scenarios.

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