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Assessment of Latent Heat Reservoirs for Thermal Management of QCW Laser Diodes

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1. Introduction:

There is great interest in improving the thermal management of laser diodes intended for use as pumps in inertial confinement fusion systems. Laser diode power is currently constrained by heat dissipation in the diodes. Diodes typically dissipate a quantity of heat that is comparable to their optical power output. This heating of the diode junction causes a thermal rollover that prevents the output power from scaling linearly with current drive, and also results in reliability limits due to catastrophic failure at diode mirror facets. For the pulsed, quasi-continuous wave (QCW) operating mode employed for LIFE and certain DOD applications, ~5 kW/cm^2 of heat must be removed on timescales of ~100µs, which is determined by thermal paths located within ~200µm of the laser junction. For these reasons, QCW thermal management is extremely challenging. Reducing the diode junction temperature enables more efficient operation, reduced thermal chirp, and operation at higher output power without compromised reliability—which improves the diode costs as measured in $/W.

We have proposed the use of latent heat reservoirs to improve thermal management of diodes used in pulsed, quasi-continuous wave (QCW) operation. Our basic concept involves placement of a reservoir of low-melting-point metal within a few hundred microns of the laser junction, as in Fig. 1-1. This metal's latent heat of fusion maintains a nearly constant temperature (like a cold plate) in the very near vicinity of the diode junction. This cold reservoir creates large thermal gradients, which in turn are anticipated to drive a large heat flow from the diode. In contrast, conventional QCW devices rely on thermal diffusion into a large solid mass which cannot be held at a fixed temperature, which significantly limits the thermal extraction.

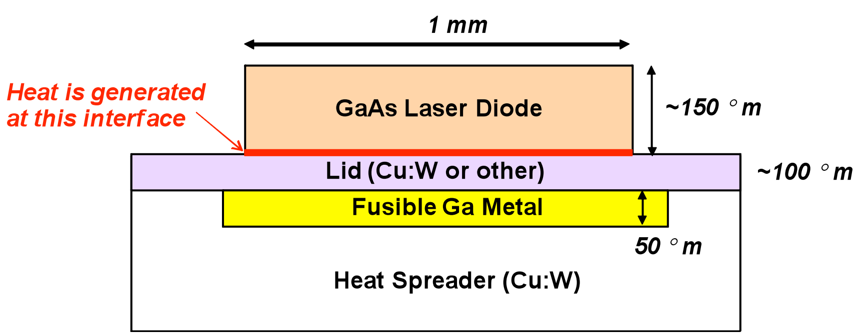

Fig. 1-1: Conceptual Device Structure. The device extends ~1 cm out of the plane.

Our operational concept involves phase changes within the reservoir during every QCW pulse. During the early portion of the pulse, heating of the diode and its surrounding material initiates melting within the latent heat reservoir. This phase change results in a near-constant reservoir temperature that facilitates heat transfer. During the long (~100 ms) time between QCW pulses, the reservoir metal resolidifies.

A simple back-of-the-envelope calculation based on Gallium metal shows that a 50 µm thick Gallium reservoir is sufficient to absorb all heat generated by a 350µs pulse at 5 kW/cm^2. While this calculation shows that a latent heat reservoir can provide sufficient capacity to handle the magnitude of heat generated, it does not address the transient change in the diode junction temperature, which depends on details the heat flow into and through the reservoir. For this reason, we undertook a set of numerical experiments to quantitatively assess the impact of latent heat reservoirs on junction temperature. This report documents the results of these simulations.

2. Methodology:

We used two simulation codes to model thermal conduction in laser diode packages. The commercial code COMSOL was used for 1- and 2-dimensional analyses. We also used a custom 1-dimensional lumped RC solver (Heat1D) as a check on the COMSOL 1D results. 1D results from these two codes were in excellent agreement for both the temporal evolution and the spatial profile (at fixed time) of the junction temperature.

We simulate the phase transition as a rectangular increase in the heat capacity of the latent heat material over a small temperature range. This effective heat capacity method is well-known in the literature.[1] Fig. 2-1 shows an example of how this method is employed.

Generically, the COMSOL code has been validated against a number of thermal conduction problems.[2,3,4] Heat1D has been validated against analytical solutions for a heat plane source sandwiched between two semi-infinite slabs,[5] and against results from finite element solvers such as Quickfield for more complicated structures. We specifically validated our methods for the case of phase transitions by comparing results from both codes against the analytic solution for melting of a semi-infinite slab of gallium, as described by the von Neumann results for material with an abrupt melting point, and thermal properties that are constant except across the phase transition. The analytic solution is available in [1]. The code simulations show close agreement with the von Neumann solutions, provided that the melting temperature range used in the codes was sufficiently narrow (Fig. 2-2).

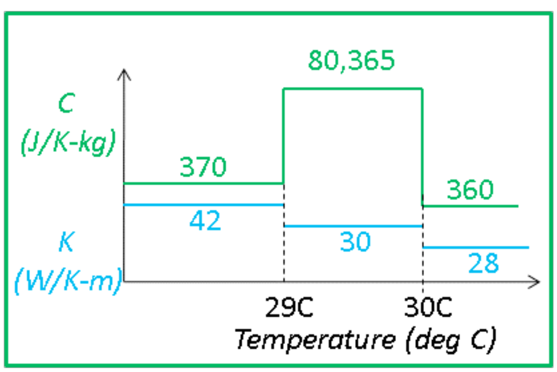

Fig. 2-1: Gallium-like Material used for code validation against von Neumann solutions

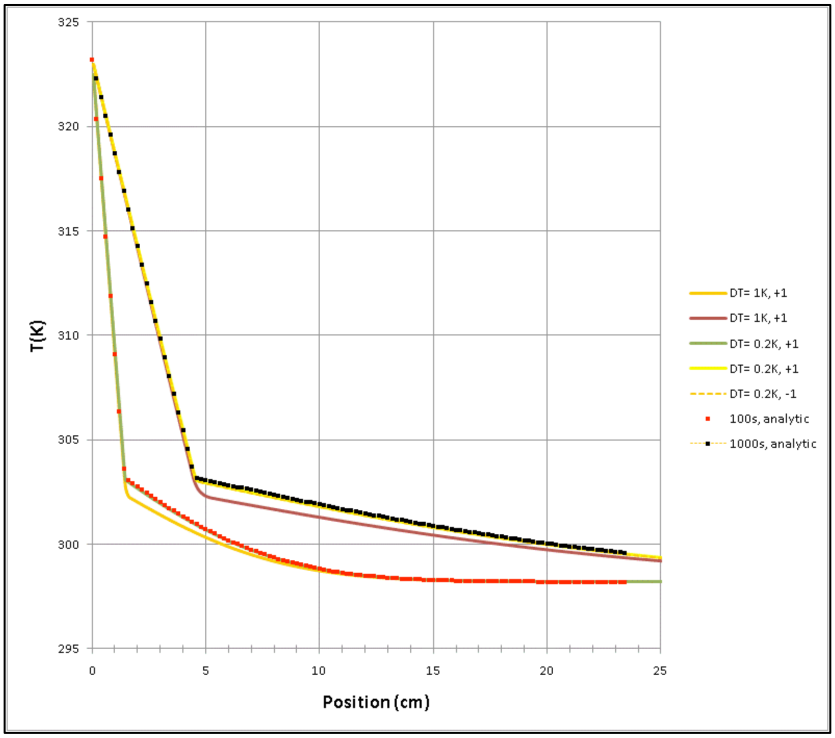

Fig. 2-2: Analytic (points) and Heat1D (lines) solutions for temperature vs. position for the von Neumann melting problem with the material of Fig. 2-1, under a sudden interface temperature change from 25 to 50C. Different lines correspond to different times after the temperature change , and to different widths DT of the latent heat "spike" representing the phase transition. DT=1K corresponds precisely to Fig. 2-1, and DT=0.2K corresponds to a narrower melting range from 29.8 to 30 C.

3. One-dimensional Structures

We simulated a typical laser structure that is depicted in Fig. 3-1. The laser diode chip comprises an active AlGaAs layer in which heat is uniformly generated, attached to a GaAs substrate. The chip is sandwiched between a CuW heat sink and a copper electrical contact, using appropriate solder bonds. We simulated performance of this basic structure with and without a latent heat reservoir comprised of a thin layer of Gallium. While the choice of gallium fixes the melting point and thus the operating temperature of our device, we note that other alloys are available with both lower and higher melting points (e.g.; from Indium Corporation), so that the operating temperature of our design could be tuned. We confined our simulations to Gallium because its thermal coefficients are readily available.

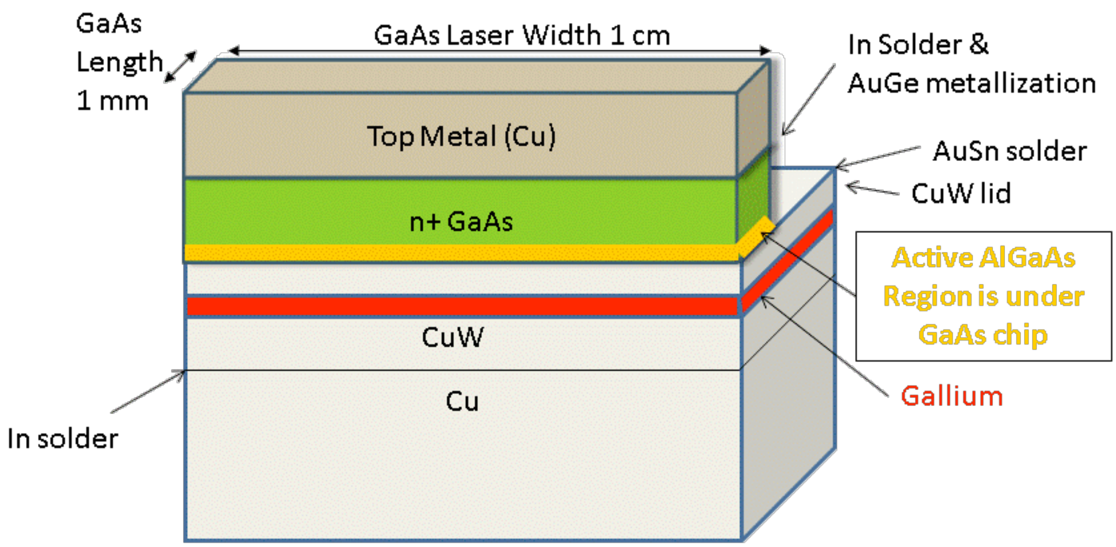

Fig. 3-1: Laser Diode Package Structure

The material properties used in our simulations are shown in Fig. 3-2. The figure shows the layer stack along the vertical direction of Fig. 3-1, and also shows the thermal properties used for these materials, when temperature-dependence was ignored. Simulations which included the temperature dependence of these materials showed nearly identical results to those which included only the temperature dependence of the Gallium.

These temperature-independent material properties at 300 K were obtained from the CRC Handbook for Au and Cu, from Adachi for GaAs and AlGaAs,[6] from Sumitomo for CuW, and from [7] for AuSn. Temperature-dependent material properties were obtained from polynomial fits to the metal data, using Adachi's formulae to represent AlGaAs, and using a composite model[8,9] and separate Cu and W polynomial models to represent CuW.

The lower boundary condition was modeled as a fixed temperature. The upper boundary condition was modeled as convective transport in air to a bath at fixed temperature when using COMSOL. Heat1D modeled the upper boundary as a thermal resistance of 5x104 K/W connected to a fixed temperature. Because heat flow barely penetrates to the upper boundary on the timescales of our simulations, the upper boundary condition had a very small effect on the junction temperature rise. The boundary fixed temperatures were usually set equal to the initial (uniform) temperature of the structure for transient simulations.

Material	thickness (um)	Basic Model, 300 K		
		rho (g/cc)	C (J/K-kg)	K (W/m-K)
air	infinite	convection or insulating boundary condition		
top metal copper	50	8.96	386.99	398.00
indium	5	7.31	233	81.58
AuGe	2	14.7	131	44.00
n+ GaAs	140	5.317	322.00	44.00
AlGaAs clad & active	3.6	4.539	381.50	10.80
Au	1	19.32	127.99	301.00
AuSn	5	14.51	129	57.30
CuW lid	100	17	160.00	175.00
Ga	50	See "gallium" phase change material below		
CuW	300	17	160.00	175.00
indium	5	7.31	243	81.58
Cu	1000	8.96	386.99	398.00
bottom surface is fixed temperature boundary				

temp range (K)	Thermal Properties employed for Gallium			
	Phase	rho (g/cc)	C (J/K-kg)	K (W/m-K)
T<302	Solid	5.904	370.9	40.6
T=302~303 K	Phase Change	6.095	80,561	35.7
T>303	Liquid	6.116	360	28.1

Fig. 3-2: Top: Layer stack for the structure of Fig. 3-1. Thermal properties of materials are shown, and color coding corresponds to the colors in Fig. 3-1.
Bottom: Thermal properties used for Gallium. The green highlight shows the increased heat capacity that represents the latent heat of fusion.

For 1D simulations, we calculated the transient heat flow in the vertical direction. The heat load was a 500 W heat step function applied uniformly to the AlGaAs layer of Figs. 3-1 and 3-2. Note from Fig. 3-1 that our cross-sectional area is 0.1 cm^2, so the heat flux is 5 kW/cm^2. The utility of the latent heat reservoir was assessed by comparing the AlGaAs temperature adjacent to the CuW lid for the cases with and without a latent heat reservoir.

4. Results of 1D Simulations

Fig. 4-1 shows typical 1D simulation results for the structure described above, using material properties which are temperature-independent (excepting the phase transition) as shown in Fig. 3-2. The salient features of the simulation are as follows:

i. The gallium reservoir introduces a steep temperature gradient at the interface between the Ga and the CuW lid. The “quasi-pinning” of this interface temperature to the gallium melting point is the desired effect
ii. The maximum temperature occurs at the laser junction (at position = 200 μm in the figure). The use of the reservoir reduces the junction temperature rise by ~2.5K for a 500W, 360 μs heat pulse.

iii. The COMSOL and Heat1D simulation results are in close agreement. The differences in the top Cu layer are attributable to the different boundary conditions implemented in these two simulators.

iv. The same simulation extended to heat pulse durations of 1000 µs show a similar reduction in junction temperature, by only 2.1 K. The junction temperature reductions predicted by both simulators is very similar (2.1 vs. 2.6 K).

v. The same simulation extended to heat pulse durations of 1000 µs shows a larger ABSOLUTE deviation in junction temperature (2K) between COMSOL and Heat1D than at 360 µs, due to the increased importance of the top layer boundary conditions.

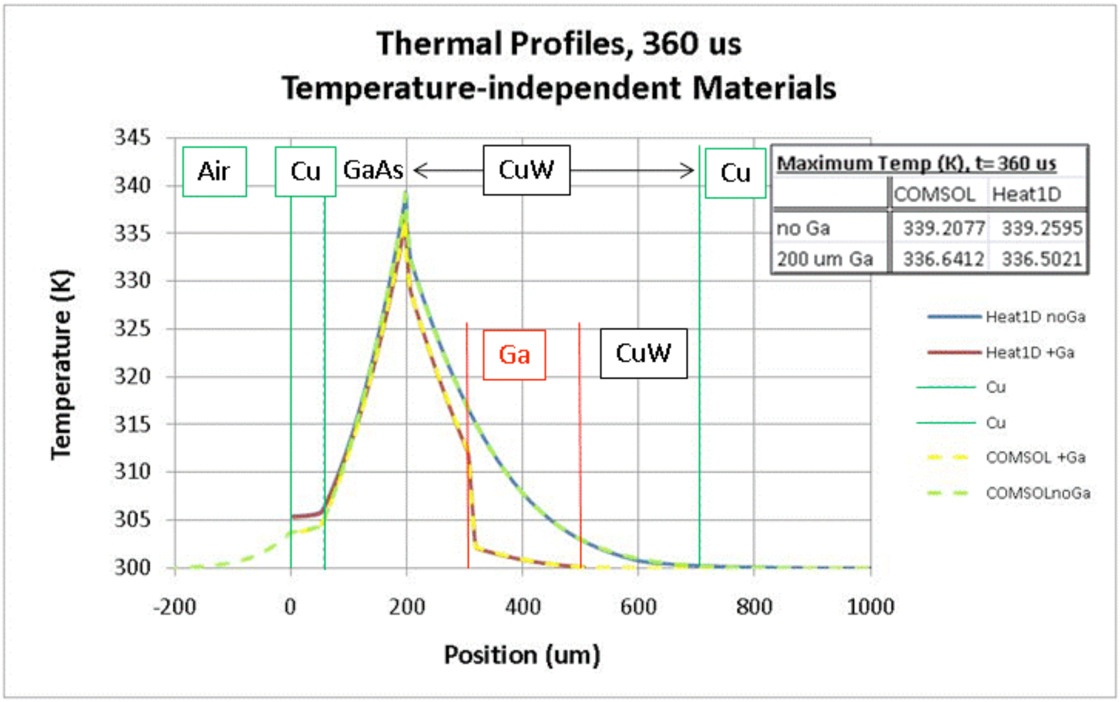

Fig. 4-1: Spatial temperature profiles after a 360 µs, 500 W heat pulse with a 100 µm lid and with and without a 200µm Ga reservoir. Dashed lines show COMSOL results and solid lines show Heat1D results. Vertical lines show interfaces between different materials (Cu, CuW, GaAs, Ga, Cu). The initial temperature is 300 K for the entire structure. The inset shows the maximum (junction) temperatures obtained from the simulators with and without the reservoir.

Results obtained with temperature-dependent thermal properties for the materials suggested a slightly larger reduction in junction temperature, of ~3 K.

We attempted to optimize the performance of the reservoir by adjusting the thicknesses of the Gallium and the CuW lid. These changes had some impact—the improvement in junction temperature rise was as large as ~6.7K. The magnitude of the improvement exhibits a complex dependence on heating magnitude, heating time, and lid details, as summarized in Tables 4-I and4-II for heat loads of 500W and 250W respectively; these results were obtained using temperature-dependent materials properties. The explanation for these phenomena involves the relative rate of heat transport across the reservoir material (as compared to the lid material) and the displacement of the liquid/solid boundary in the reservoir.

Table 4-I: Junction Temperature Reduction for 500W Heat Pulse and 200μm Reservoir

Lid Properties		ΔTmax (K)		
Thickness (μm)	Material	t=200 μs	t=360 μs	t=1000 μs
100	CuW	1.25	3.09	3.30
20	CuW	5.29	5.30	-0.28
10	Diamond Type II	6.69	6.08	-0.53
0	none	6.10	5.21	

Table 4-II: Junction Temperature Reduction for 250W Heat Pulse and Various Reservoirs

Gallium	Lid Properties		ΔTmax (K)	250 W pulse
Thickness (um)	Thickness (um)	Material	t=360 μs	t=1000 μs
200	100	CuW	3.62	3.62
200	20	CuW	5.05	5.37
200	10	Diamond Type II	5.99	5.90
100	0	none	5.87	5.51
100	10	Diamond Type II	6.00	5.96
50	10	Diamond Type II	6.07	6.11

The temperature profiles corresponding to Table 4-II are shown in Fig. 4-2. Temperature pinning to the Ga reservoir melting point is evident in sharp thermal gradients at the Gallium melt boundary. The fundamental limit appears to be the finite thermal conductivity of the liquid Ga, which impedes heat flow from the diode junction to the Ga liquid/solid interface (which is pinned to the melting point). As the solid/liquid interface moves away from the diode junction, the reservoir becomes less effective at removing heat due to the increasing thermal impedance from the reservoir (solid Ga) to the junction.

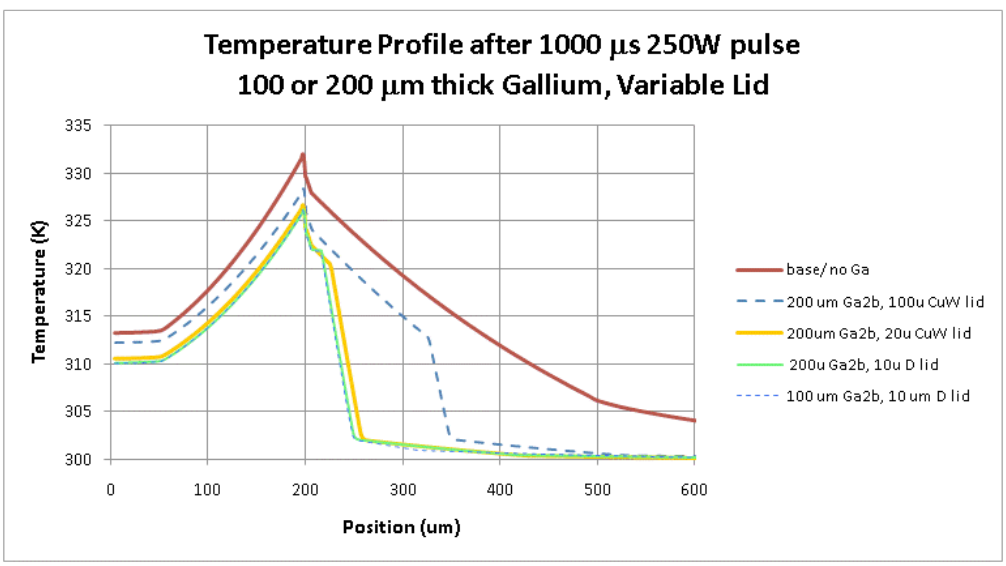

Fig. 4-2: Temperature Profiles for Various Reservoir Thicknesses and Lid Configurations, for a 1 ms, 250W heat pulse. The simulations use temperature-dependent material properties and CuW or Type-II diamond lids.

The effect of the moving solid boundary causes a complex time dependence of the junction temperature (Fig. 4-3), which depends on the magnitude of the heat load. At short times, before the reservoir begins to melt, structures without a reservoir perform significantly better due to the better thermal behavior of CuW as compared to Ga. As the Ga begins to melt, a sharp reduction in the rate of junction rise occurs, and shortly thereafter structures with reservoirs show improved performance (reduced junction temperature). With continued melting, however, the thermal impedance to the cold region of the structure increases due to displacement of the melt boundary, which decreases the enhancement associated with temperature pinning. At sufficiently long times, all the Ga melts and its increased thermal resistance relative to CuW results in worse overall performance.

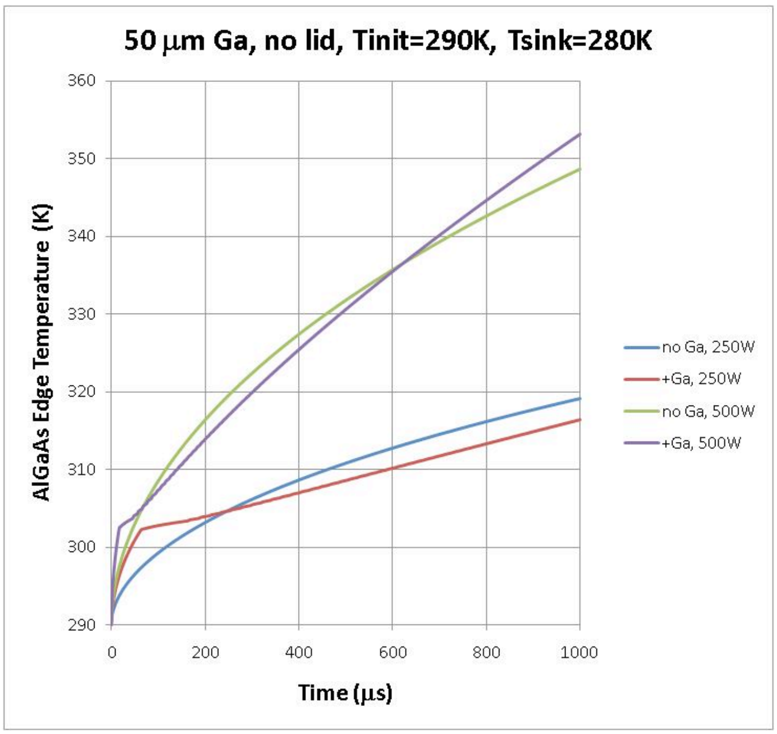

Fig. 4-3: Time Dependence of the Junction Temperature (1D Simulation) for different heat loads, a thin Ga reservoir, and no CuW lid. The intitial condition was a uniform temperature of 290K, and the lower heat sink was held at 280K. The simulation employed temperature-dependent material properties.

We attempted to improve transport across the molten Ga by operating the bottom heat sink at a temperature below "ambient", to increase the thermal gradient and heat flow across the Gallium. Even with heat sink temperatures at 260K (30K below the 290K ambient initial conditions), the improvement in junction temperature rise remained at ~3K or less.

Based on the above numerical experiments, we conclude that a **planar** latent heat reservoir structure can improve the junction temperature rise by as much as 6.6K for aggressive designs that use very thin lids (20 μm) which may not be readily manufacturable, and by as much as 3.6K for thicker lids.

5. 2D Structure Simulations

The 1D simulations of planar structures suggest that planar latent heat reservoirs are limited by their ability to transport heat from the junction to the solid-liquid interface. To improve this transport, we propose to use a radiator-like structure in which the lid material protrudes fins into the latent heat reservoir. This structure reduces the transport distance, “short circuits” the liquid Ga with fin material, and increases the effective surface area for heat transport into the reservoir.

To explore this concept, we studied the structure shown in Fig. 5-1, in which 40 μm thick fins of copper protrude 200 μm into a Ga reservoir. The thickness of Ga between the fins is 15 μm. 2D simulations were performed for the thermal profiles using COMSOL, for 500W heat pulses of 360 and 1000 μs duration. Our results show that this approach reduces the junction temperature rise by 6~9K, as compared to a junction mounted directly on a Cu submount.

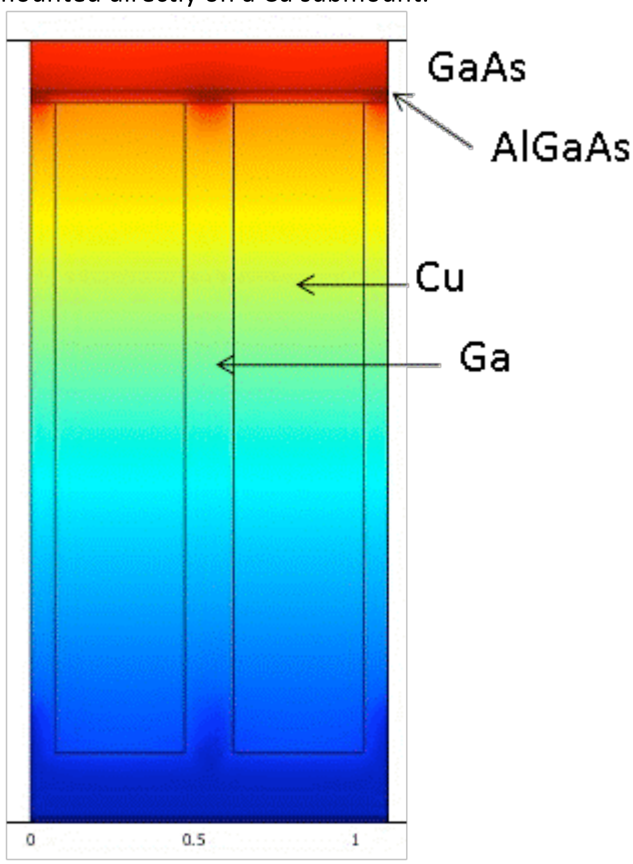

Fig. 5-1: Simulated thermal profile for a 2D fin structure after a 500W, 1ms heat pulse . The coldest temperature (blue) is 300K and hottest temperature is 337K (brown).

We observed that the region of the junction above the copper was always slightly cooler than the region directly above gallium. This suggests that some optimization may be achieved by introducing a small thickness of copper between the gallium and the AlGaAs. Alternatively, since a high-power laser bar consists of wide active stripes with non-lasing regions between them, one might mount the bar such that the thin- or no-copper regions lie directly above the non-lasing areas.

An alternative structure which may achieve the same functionality as the fins would be to employ a porous copper medium impregnated with fusible metal. The copper medium could be a copper foam, or copper "wool" made from many interwoven copper filaments.

6. Notes on Practical Issues

While the purpose of this study was primarily to assess the effectiveness of an ideal latent heat reservoir, we did consider several of the practical issues which would arise in fabricating useable structures. This section briefly describes mitigation strategies for potential issues with the reservoir.

i. Corrosion

Gallium is known to be highly corrosive to other metals such as copper and aluminum. Other low-temperature fusible metals typically contain Ga in the alloy and will exhibit similar effects. To prevent long-term reliability issues, we envision that the surfaces containing the fusible metal will be coated with a non-corrodible material. Examples include nickel plating, or coating with diamond-like carbon. Alternatively, portions of the reservoir container could be fabricated from non-metallic materials such as silicon, beryllium oxide, or various ceramics.

ii. Expansion/contraction during phase transition

Liquid metals (Ga, Hg) undergo large expansions when they melt. The device structure must be able to reliably accommodate this expansion without introducing large stresses in the laser diode chip. We envision two approaches to this:

a. Allow some headspace above the reservoir, into which molten metal can flow. Gravity can be used to ensure that the metal does not flow away from the interface to be cooled. This concept is illustrated in Fig. 6-1.

b. Confine the reservoir with a flexible membrane at the interface below the diode. This could be accomplished with a thin silicon membrane, for instance.

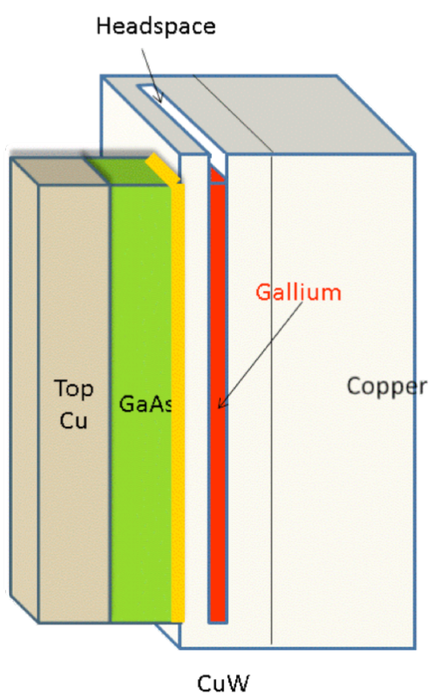

Fig. 6-1: Cutaway view of structure illustrating use of a headspace to accommodate reservoir expansion during melting.

iii. Melt initiation

It is known that gallium can be supercooled—that is, if cooled slowly below its melting point, it will not re-solidify unless seeded with solid material. We expect to avoid this issue by designing a reservoir which never completely melts. The constant presence of solid material should provide a seed to enable resolidification between QCW laser pulses. Under these circumstances, we expect resolidification to be a rapid process (on timescales of ~1 μs) based on published reports.[10]

7. Summary and Conclusions

A latent heat reservoir can reduce the maximum temperature rise in a laser diode junction under QCW operation. For heat pulses of 250~500W and duration 200~1000 μs, simulations show junction temperature improvements from 3 to 6.7K in planar structures. The use of a 2D fin structure can improve the performance of the latent heat reservoir, achieving up to 9K improvement in junction temperature when compared to a junction mounted directly on a Cu heat sink.

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