

IBM Research Report

High Performance Liquid Metal Thermal Interface for Large Volume Production

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Abstract

Thermal Interface Materials (TIMs) between microprocessors and heat-sinks are crucial for cooling high performance components at today's power levels. The focus of TIMs for high power processors has been a thin highly conductive and inert layer that can withstand the thermal expansion mismatch between silicon chips and copper based lids or heat-sinks. This work focuses on a Liquid Metal Thermal Interface (LMTI) developed for high volume production in computer systems.

Compared to the best polymer thermal interface, LMTI boosts the interface conductivity by an order of magnitude. It also minimizes issues of mechanical compliance and load. The paper examines performance of LMTI and reliability aspects that include providing good wetting of the liquid and protection from oxidation and corrosion. It also presents examples of temperature gains obtained with LMTI in actual products, as well as a demonstration of cooling capability in excess of 750 W/cm² obtained in conjunction with a water cooled heat-sink.

Keywords: Thermal interface, Chip cooling, Liquid metal, Low melt alloy, Gallium Indium, Processor thermal management

Introduction

The trend toward high power computer processors urges the development of packaging technologies able to dissipate concentrated heat generated in the processors, in excess of 100 W/cm² (Watts per centimeter square). An optimized thermal interface between processor and heat dissipating system (heat-sinks) is a key component. In particular, the Thermal Interface Material (TIM) must meet several requirements:

1. Low thermal resistance between processor and heat-sink (and/or copper lid or copper cold plate)
2. Mechanical compliance between processor and heat-sink to accommodate differential thermal expansion and mechanical strains
3. Stability over time and under stress; in particular, the TIM material must not degrade or allow void formation, between processor and heat-sink.

4. Manufacturable in high volume in a cost-effective manner.

Traditional TIMs have included polymers (pastes or gels) filled with thermally conductive particles, but the thermal conductivity of these materials is rather low, on the order of 1 to 5 W/mC (Watt per meter per Degree C). The past 5 years have seen a migration from paste to metal which offers an order of magnitude larger thermal conductivity. Manufacturing constraints have largely limited the use of metal TIMs to "lidded-module" packages. Such a package consists of a processor (with a substrate for electrical connections) that is soldered to a copper lid. The copper lid acts as a heat-spreader and the metal solder is referred to as TIM1. The copper lid is butted against a heat-sink with a grease interface, referred to as TIM2.

Our work has focused on the development of a Liquid Metal Thermal Interface (LMTI), that can be used in high volume production, as TIM1, TIM2, or directly between a bare die processor and a heat-sink

(referred to as TIM in the ensuing text). Liquid metal has been sparsely considered in the past for cooling electronic components [1-9]. Performance of this novel thermal interface is the highest we have thus far observed. We shall present the unique benefits of LMTI and a selection of the technical challenges that we faced and solved along the road to qualification for high volume production.

Performance

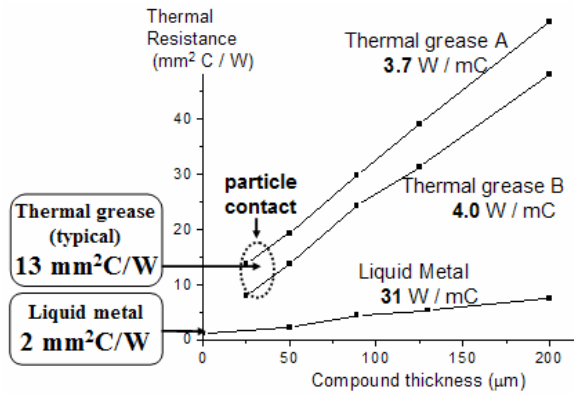


Figure 1: Thermal performance of Liquid Metal versus thermal greases

Liquid Metal Thermal Interface (LMTI) refers to a small group of eutectic alloys, based on Gallium, that remain liquid at room temperature and under normal operation of a computer. Eutectics of GaIn, GaInSn and GaInSnZn are the main candidates [6], with solid-liquid transition temperatures between 9 and 15C, and thermal conductivity around 30 W/mC. Fig.1 shows results from our thermal conductivity measurements for liquid metal and thermal grease. The thermal resistance is plotted versus the thickness of the material and the thermal conductivity is extracted from the slope of the data. The data also indicates that the thermal resistance at zero gap (extrapolated from the data) is not zero, but has a final value indicative of non-perfect contact between the TIM and the surface of the solid. For liquid metal between two very flat surfaces and at minimum gap (contact, or less than 10 micrometer average gap), the minimum thermal resistance is between 1 and 2 mm²C/W. For grease, the minimum gap is dictated primarily by the size of the conducting particle fillers, and is around 25 micrometers for high performance compound under high load (100 psi or more). The corresponding minimum thermal resistance is about 13 mm²C/W. In general, LMTI offers between half

and one order of magnitude improvement in thermal resistance when compared to grease.

Figure 2 shows the typical improvement found in product-like application, consisting of a lidded processor module, a TIM2, and finned heat-sink. Processor dimensions are 15 by 20 mm, and lid thickness is 2mm. The data shows the measured thermal resistance (processor temperature rise over input power, in C/W) for varying heat-sink air-flow, and for two different types of TIM2: a phase-change [10] material (particulate filled polymer with a melting point around 50C), and liquid metal. The improvement in thermal resistance afforded by LMTI is 0.1 C/W and corresponds to a typical 10C at 100W.

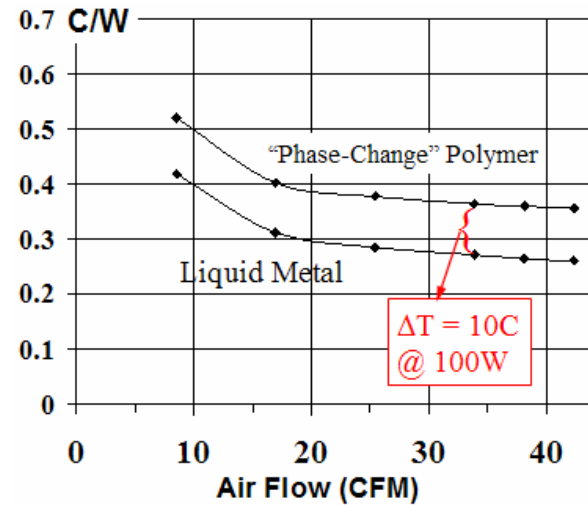


Figure 2: Thermal resistance of a standard air-cooled module as a function of TIM and airflow

Bond line thickness (thickness of TIM) is an important parameter for grease and solder metal thermal interfaces, which must be controlled with a given load and/or within a given thickness window for good and reliable performance [8]. A paradigm shift is introduced for LMTI: we find that the best performance for LMTI is obtained at contact, which is achievable under low load on the order of one psi. LMTI acts as a lubricant that reduces shear forces to practically zero. When properly assembled with adequate wetting layers (see below), we find no evidence of pump-out, in contrast to thermal grease. Furthermore, the combination of a thin bond line and high capillary forces for LMTI results in a remarkable resistance to shock and vibrations: our thermal vehicles have been tested under extreme acceleration (up to 1500 g of acceleration) without fail.

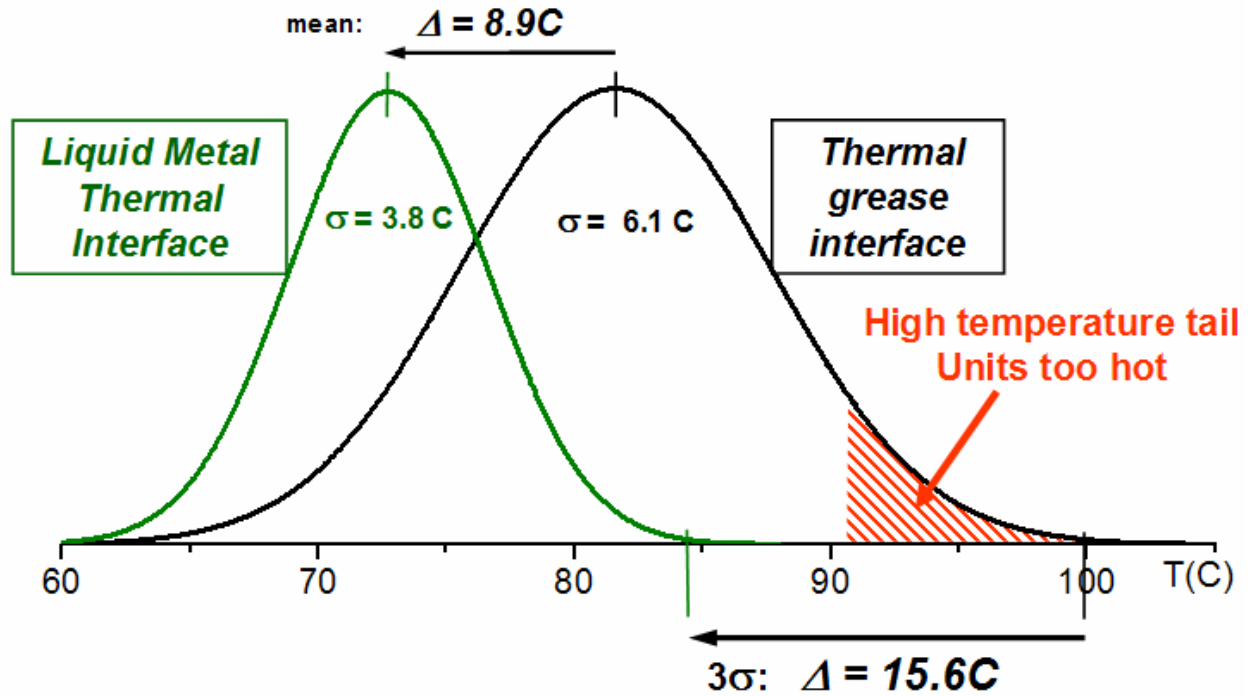


Figure 3: Histograms of processor temperature for thermal grease and Liquid Metal Thermal Interface (LMTI)

Figure 3 highlights another key benefit of LMTI versus grease thermal paste, the narrowing in the distribution in thermal resistance. In this product study, the processor bare die is approximately 12 x 13 mm, and is directly butted against a vapor chamber heat-sink. Processor power is approximately 100W. The figure shows histogram of processor temperatures obtained for 2 TIMs, thermal grease and LMTI. LMTI brings –as expected- a reduction of the mean processor temperature of about 9C. In addition, the standard deviation narrows from 6.1C with grease to 3.8C with LMTI. This brings an important reduction of the high-temperature tail of the distribution, which directly impacts manufacturing yield and reliability. The data shows a large reduction of temperature, over 15C, at the 3 sigma point of the distribution. In this study, the width of temperature histogram depends not only on the variability of the thermal interface, but also on several other several factors including variability in chip power, in calibration of the imbedded temperature sensor, and in vapor chamber heat-sink. In our particular case, independent studies attribute at least 2 C of the standard deviation to variability in vapor chamber heat-sink, and a similar value to processor variability. It ensues that the remainder of the variability, attributable to LMTI only, is probably well under 1C. Indeed, this and other studies point to the better

reproducibility of good LMTI performance, and are indicative of a wider process latitude than thermal grease. In particular, the tolerance to non-planar or non-coplanar surfaces is widened because of the high thermal conductivity of liquid metal.

Liquid Metal Failure Modes

The predominant failure modes of liquid metal interfaces observed during testing include: de-wetting, alloying and corrosion. They are related in that corrosion and alloying lead to de-wetting or dry out, and that de-wetting and dry-out accelerate corrosion. On the other hand, a properly wetted surface resists corrosion and maintains a good thermal bond. Wetting in this context is similar to the wetting of solder. A metal to metal contact yields the best performance in terms of thermal contact and resistance to corrosion.

As in the solder case the presence of surface oxide or contamination impedes the wetting process. Wetting methods were investigated for both heat sink and chip, with the chip surface being the most challenging. A variety of surface treatment methods were evaluated to determine their effect on wetting. These include hydrogen or hydroxyl termination,

molecular mono layers of various organic functional groups, attached metallic layers of metal particles (gold, Ni, W), surface roughening, and thin polymer layers. Without exception, these methods were found ineffective. Those which showed effective initial wetting degraded later when exposed to stress.

The consistency and composition of the liquid metallic interface was experimentally varied using fillers and alloys. Particulate fillers such as graphite, diamond, nickel, tungsten and many others were explored. These had little or no effect on wetting. They adversely affected bond-line and resulted in reduced thermal conductivity. Most mixtures had a consistency similar to wet sand and had poor flow characteristics. A variety of mixing methods were investigated including vacuum mixing and ultrasonic mixing.

The direct metal to metal contact was found to be the best solution to achieve wetting. Metals which have low solubility in gallium and indium were chosen. These surface coatings also tested well for corrosion resistance. In order to achieve a stable oxide free surface, these materials were deposited and immediately coated with a soluble metal to preserve the surface. Once applied, the soluble metal dissolves into the liquid metal leaving a direct metal to metal contact.

Short term performance of the interface comprising the liquid metal and surface coatings described above was excellent. Severe temperature/humidity stress testing however showed the presence of corrosion. Gallium oxide is the primary corrosion product. When present, it typically forms at the interface to the chip or heat sink and is usually comprised of Ga_2O_3 (see Figure 4). This corrosion initially results in de wetting. Extensive corrosion will result in dry out and failure of the interface. Corrosion is accelerated above 60% relative humidity and at high temperatures 60 degrees C and up. Many remedies to corrosion were investigated. These included cathodic protection, vapor corrosion inhibitors, additives, reformulation and encapsulation. The most effective remedy was found to be a hermetic containment to maintain a moisture free environment. Using these methods the interface was found to pass qualification testing to several thousand hours of stress at 85% relative humidity and 85 degree C conditions.

Failure modes also include contact with incompatible materials. Gallium is particularly corrosive to aluminum. Components of the liquid metal alloy with

copper and nickel as well. Furthermore, nickel is soluble in small amounts in gallium. Chrome is significantly less soluble than nickel, but dissolves trace amounts in liquid metal. Finally, residuals from cleaning can accelerate corrosion. Use of fluxes and cleaning surface agents such as HCl can leave residual chlorides which have been found accelerate corrosion. For these reasons, it is important that the coated surfaces to be joined with liquid metal be contamination and defect free. Cracks and coating defects are to be avoided.

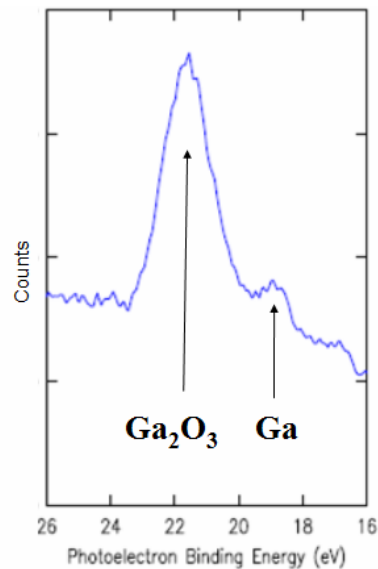


Figure 4: XPS of Liquid metal dewet. A thin layer of Ga_2O_3 forms at the interface, 6 to 12 Angstrom thick. This layer is non wetting, and allows the rest of liquid metal to pull away.

Initial concerns were raised with respect to safety and diffusion of liquid metal components in to the silicon. The liquid metal components are both safe from a personnel exposure point of view and ROHS compliant. SIMS was used to demonstrate that diffusion of liquid metal components into silicon with time and temperature is too small to be an issue over the lifetime of the product.

Reliability testing and results

We have conducted a variety of accelerated tests to qualify LMTI for reliability to high volume production. Our main test vehicles are based on a silicon test chip mounted on a ceramic substrate, and

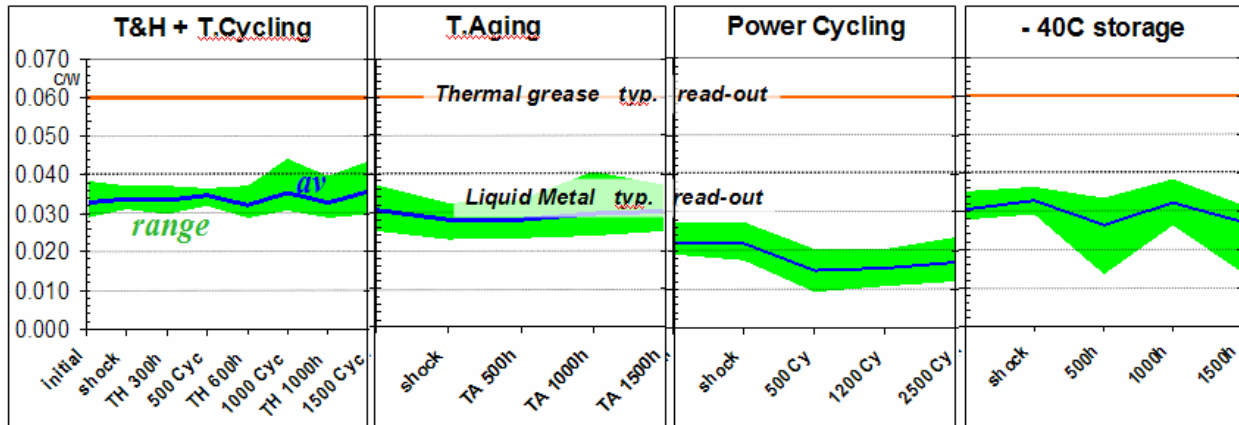


Figure 5: Example of thermal measurements done for qualification tests on thermal vehicles that incorporated a liquid metal thermal interface. **Note that the thermal resistance values include chip, interface and lid.**

containing four resistive heaters, and several temperature sensors in close proximity to the heaters. The back of the silicon chip is butted against a 3mm standard nickel plated Copper lid with a GaInSn eutectic liquid metal in between. Prior to assembly, both chip and lids are coated. An electrical power P of approximately 150 W is applied to the silicon chip heaters, and cooling is provided to the exposed side of the copper lid. The copper lid contains a thermocouple which allows measurement of temperature difference ΔT between the heated chip and the cooled lid, which includes the thermal interface. Figure 5 presents results of measured $\Delta T/P$ in C/W at various stages along several tests. For approximate calibration of the units that we display, 0.06 C/W (bold line near top of scale) corresponds to a typical grease thermal interface at 13 to 15mm²C/W. Our measurements are centered around 0.03C/W which corresponds to approximately 2mm²C/W.

Figure 5 summarizes results for 4 groups of accelerated tests, and for a total of over 50 test vehicles. For each group of tests, initial measurement of $\Delta T/P$ is performed after assembly, and after exposure to shock and vibrations, including shocks at an acceleration of 1500 g. The subsequent tests include:

1. Exposure to temperature & humidity (T&H at 85C & 85% RH) interspersed by thermal cycles from 10 to 110C
2. Temperature Aging (TA) test at 125C
3. Power Cycling (PC) tests where the chip is powered to cycle its temperature between 10 and 110C

4. Low temperature “Storage” tests, at -40C.

The overall measurement results center very much around 0.03C/W, with no substantial trend to failure along any of the test groups. The residual variability is mostly attributable to performance limits of equipment and vehicles used for this reliability and qualification work.

Assembly and manufacturing processes

Assembly of the liquid metal interface involves the steps of coating the heat sink and chip surfaces, placement of containment and dispense of liquid metal. Cleanliness is an essential element of good assembly practice. Liquid metal is easily spread to unwanted places if good handling practice is not exercised. Soap and water are effective in removing the material from work surfaces etc. Component contact surfaces should be free of particulates and other contaminants. If cleaning is necessary, organic solvents have been found most effective used with cotton swabs and wipes.

Coating of the heat sink and chip surfaces was found to be possible by sputtering, evaporation, jet process and foil transfer process [11]. For most applications sputtering is the preferred method. Liquid metal dispense has been achieved with a variety of methods including droplet dispense, mechanical spreading, and ultrasonic spreading. Key aspects of the dispensing operation include the ability to dispense a precise quantity and spreading the material over the surfaces to be joined. The total amount dispensed is chosen to be larger than the target bond line to be

covered plus overflow. Over fill capacity should be factored into the design.

Rework is a commonly expressed concern. We routinely demonstrate that rework is both practical and possible in the field. Pre-packaging of disposable materials and simple cleanliness precautions are adequate to allow field rework.

Conclusions and future directions

Current focus has been the application to high power processor chips with areas ranging from 0.5 cm² to 4 cm². Future applications will address applications to larger (5-10 cm²) and significantly smaller (1-50 mm²) chips at high power. A significant portion of the work described above was performed on test chips and processors mounted on ceramic substrates. More recent work addresses chips mounted on organic substrates, which are somewhat flexible and more permeable to water than ceramic substrates. It is a typical industry practice to add copper lids to chips on organic substrates in order to provide stiffness to the assembled module. It is our position that the use of lids significantly degrades the thermal performance of the overall cooling system.

We have chosen to focus on liquid metal thermal interfaces between bare chips and vapor chamber heat-sinks. Liquid metal allows room-temperature assembly, chip to vapor chamber heat-sink, and avoids the reflow requirement of solder thermal interfaces. This is a key attribute for a vapor chamber and toward flexible and cost effective manufacturing. Direct attach of the chip to the copper vapor chamber is also enabled by the inherent tolerance of the liquid metal interface to mechanical shear. In addition, the low normal force requirement allows a thin wall to the vapor chamber or heat pipe further improving performance. For chips on organic substrates, a moderate clamping force between vapor chamber and organic substrate is sufficient to limit the flexing of the module under thermal stress. It is our position that direct attach of the chip to a vapor chamber heat sink or mini channel water cooled heat sink using a liquid metal interface represents the optimum in cooling efficiency.

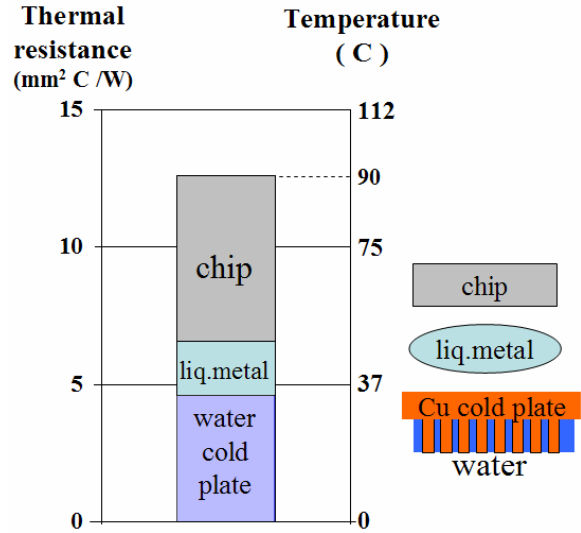


Figure 6: Cooling 750W in a 1cm² chip with a water cold plate and a liquid metal thermal interface: thermal resistance and temperatures from chip hot area to water.

We have been able to demonstrate 750 W/cm² cooling in the laboratory using a heater chip coupled to a copper water cooled heat sink using a liquid metal interface. Figure 5 illustrates the configuration of this test, in which we supplied 750W to a 1cm² test chip, and cooled it with a temperature difference ΔT of 90C between chip and water. The test demonstrates the ability of a liquid metal thermal interface to transfer large power densities. For lesser power densities, in the range between 100 to 300 W/cm², a vapor chamber offers extremely effective heat spreading properties. The properties described above make the liquid metal interface uniquely suited to interface bare chips to vapor chamber or heat-pipe fitted heat-sinks.

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