# A Jettable and Dispensable Liquid Metal Paste as a Thermal Interface Material

Miloš Lazić
Indium Corporation
301 Woods Park Drive, Suite 301
Clinton, NY, 13323, USA
Ph: +1315-835-4900; Fax: +1 315-853-1000
Email: mlazic@indium.com

## Abstract

Metal thermal interface materials (TIMs) have been used in the electronics industry for over 20 years. The thermal performance of any TIMs is defined by their thermal conductivity, bondline thickness, and interfacial resistance. Generally, metal TIMs have very high thermal conductivity and can be applied in a thin layer. Most of the metals are hard and stiff, making interfacial resistance the biggest obstacle for metal TIMs to overcome. Over the years, many metal TIMs have been developed and used in applications to improve the performance of the components. Recently, liquid metal TIMs are getting more attention, especially in gaming and high-performance applications. They are excellent for accommodating imperfections of the materials they are connecting, but their physical properties can make application risky. To overcome this challenge, a new metal TIMs material—a liquid metal paste (LMP) TIM–has been developed.

This paper will examine this new material's thermal conductivity, viscosity, jetting, and dispensing performance compared with other existing metal TIMs, such as liquid metal. The application in mass manufacturing will be studied, with a solution to prevent leakage and provide higher thermal cycling performance (-40°C/+125°C) for LMP.

## Key words

Liquid metals, Liquid metal pastes, Metal TIMs, Thermal interface materials (TIMs), Solid-Liquid Hybrids**.**

## I. Introduction

Thermal interface materials are the key components in many electronic devices. Air is a poor thermal conductor, so whenever heat is generated and needs to be transferred, TIMs are great options to create close connections between the heat source and the heat-sink or heat spreader.

Before exploring the materials used for TIMs and their main properties, it is very important to define the classification of TIMs.

Fig. 1 shows a typical semiconductor application. TIM 1, represented as the darker blue line, illustrates the material applied in-between the integrated circuit (IC) and heat spreader, shown in yellow. TIM 2, represented by the violet line, is applied in-between the heat spreader and a heat-sink, shown in green. In applications where there are no heat spreaders, a TIM is placed between the IC and the heat-sink. The TIM is called TIM 1.5 or TIM 0.

There are many different types of TIMs and one of the key components for each of them is the thermal conductivity. Thermal conductivity is the biggest advantage of metal TIMs. Fig. 2 shows the typical thermal conductivity for some of the most common TIMs on the market. Thermal conductivity for those TIMs is in the range of 1 – 10 W/m*K.

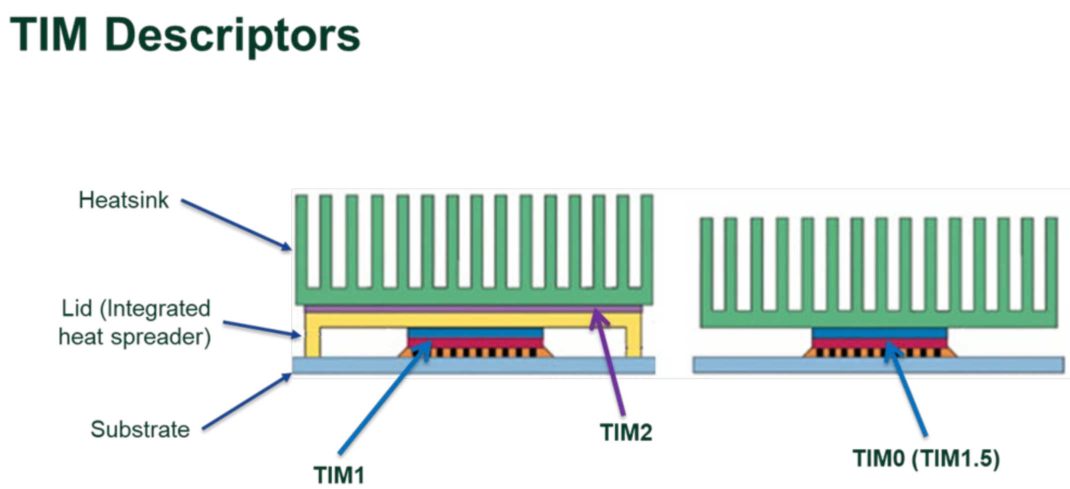



**Figure 1.** Types of TIMs.

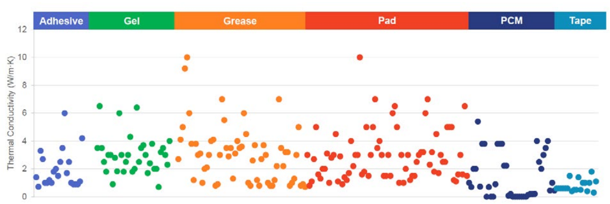



**Figure 2.** Thermal conductivity of non-metal TIMs [7].

On the other hand, thermal conductivity of metal TIMs would be in the range of 15-86 W/m*K (Fig. 3).

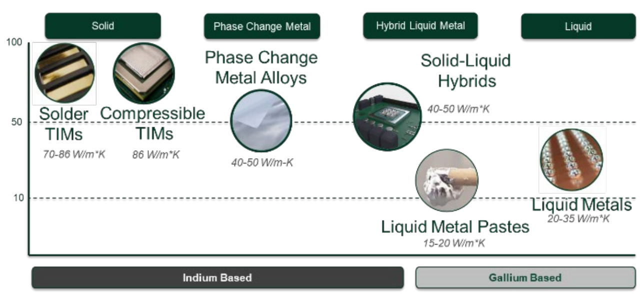



**Figure 3.** Thermal conductivity of metal TIMs.

All TIMs should have high bulk thermal conductivity since that material would have better heat transfer from the heat source. Thermal conductivity is very important, but that is not the only property that should be considered. Thermal impedance defines how the TIM will perform in the application. Thermal impedance is a combination of thermal conductivity and thermal contact resistance and can be defined by the following equation:

$$TI_T = BLT/K + R_C$$

Where:

$TI_T$ – Total thermal impedance
BLT – Bondline thickness of the TIM
K – Bulk thermal conductivity of the TIM
$R_C$ – Thermal contact resistance at the interface (Fig. 4)

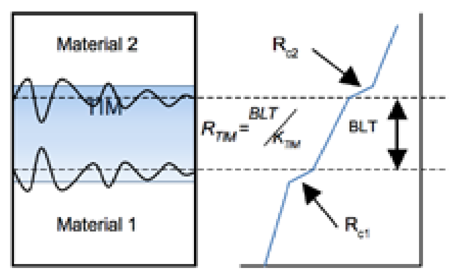



**Figure 4.** Total thermal impedance [4].

We want our TIMs to have the highest possible thermal conductivity, yet the lowest possible thermal contact resistance and bond line thickness. The biggest challenge for metals is the thermal contact resistance. Most metals are very hard and stiff, and it is hard for them to achieve closed connections among heat source, heat spreader, heat pipe or heat-sink. Indium was one of the first metals used for TIM due to its softness and ductile natures. Its primarily used as a solder TIM in TIM1 applications or as a compressible TIM in TIM2 or TIM0 (TIM1.5) applications (Fig. 1). When alloyed with tin and/or indium, gallium creates alloys that are liquid at room temperature. These alloys would not only be able to overcome interfacial resistance, a common issue with most metal TIMs, but also to adopt any imperfections—such as roughness or planarity issues—of the surfaces it connects. These benefits are the main reason why metal TIMs are the most effective when made with indium-based or gallium-based materials (Fig. 3).

In this paper, the primary focus will be on gallium-based materials with highlights on the novel liquid metal pastes (LMP).

## II. Liquid Metals

If overcoming interfacial resistance is the biggest obstacle on the road to finding the perfect TIMs, then liquid metals could be the answer to this dilemma. Fig. 5 shows how a material's thermal resistance can change with pressure when it is in a solid and a liquid phase (51In/32.5Bi/16.5Sn [MP: 60°C]). When metal is in a liquid phase, it will provide wetting on both surfaces, thus lowering interfacial resistance and providing better heat transfer. Liquid metals also have an ultra-low bondline thickness.

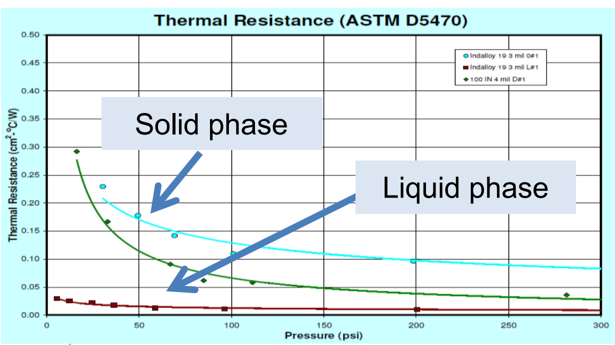



**Figure 5.** Thermal conductivity of metal TIM when it is in the solid and liquid phase.

Table 1 shows the properties of liquid metal alloys as well as properties of their base elements. Liquid metals have lower melting points and lower thermal conductivity than their base metals. They are high-density and low-viscosity materials and have low vapor pressure, which does not evaporate and cannot be inhaled.

**Table I.** Liquid metal thermal conductivity.

| Metal/ Alloy | Melting Point (°C) | Composition | Thermal Conductivity (W/mK) |
|---|---|---|---|
| Gallinstan | 11 | 66.5Ga/20.5In/13.0Sn | 35 |
| EGaIn | 16 | 75.5Ga/24.5In | 37 |
| EGaSn | 21 | 91.6Ga/8.4Sn | 28 |
| Indium | 157 | 100 In | 87 |
| Tin | 235 | 100 Sn | 73 |
| Gallium | 30 | 100 Ga | 31 |

There are several challenges to overcome when using liquid metals as TIMs. First, gallium is very aggressive to aluminum, which is very often used as a material for heat-sinks. Fig. 6 shows what a rection between aluminum and gallium would look like. A small amount of GaIn liquid metal was applied on the aluminum heat-sink. Afterward, the heat-sink was stored at 125°C for two weeks. When in contact with aluminum, gallium would go through the grain boundaries of aluminum and destroy the integrity of the material, especially at elevated temperatures.

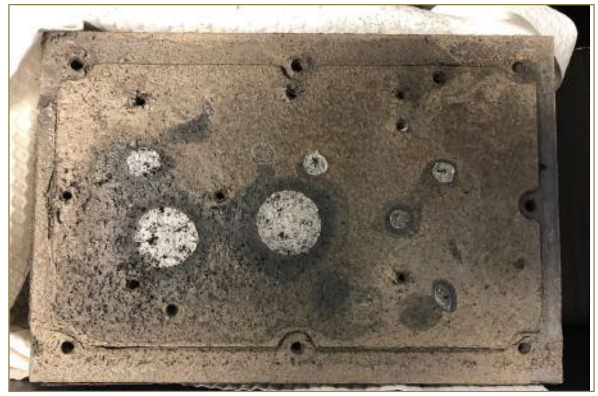


**Figure 6.** An aluminum heat-sink after exposure to gallium based liquid metal.

Liquid metals are not only thermally conductive but also electrically conductive, meaning that leaking liquid metals can short other electrical devices. Another challenge for using these materials is oxidation. Passivating oxide layers in liquid alloys are constantly disrupted allowing oxidation of the newly exposed surfaces. This oxidation can degrade the thermal contact and limit the life of the TIM. In order to use liquid metal as a TIM, the material should be contained to prevent any leaking issues and nearby components should be insulated. Fig. 7 illustrates one of the solutions for using liquid metals or LMPs as a TIM.

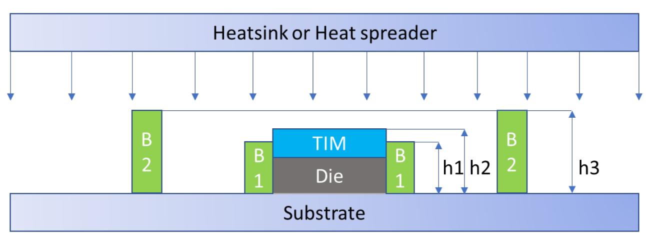
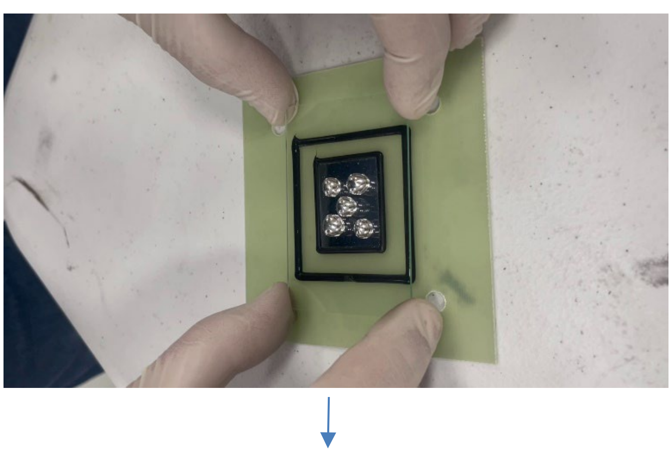



**Figure 7.** Double barrier system for liquid metals and LMPs containment.

Materials used for barriers should be electrically non-conductive. Different types of adhesives and polymers are often used for those barriers. In this case, there are two barriers (B1 and B2). B1 should be applied around the edge of the die. After that, the material will go through a recommended curing process, and it will create a solid barrier (B1). The height of B1 will also define the bondline thickness (BLT) of our TIM. In the second process, the TIM (liquid metal or LMP) and the second barrier (B2) will be applied. Both materials can be applied by dispensing or jetting. Most modern-day dispensing and jetting machines can have multiply dispensing or jetting heads, so this process can be done in the single machine. When we know the height of B1, we can easily calculate how much material (liquid metal or LMP) we should apply to fill that cavity. However, we intentionally overflow B1 to compensate for inaccuracy of the high-volume production (HVP) machineries. If the machine has a tolerance of 5%, the volume of our TIM would be in the range of 95%-105%. If the applied volume is below the calculated percent, we would end up with some air trapped in our TIM, which would have a negative impact on the thermal performance of the material. If we are above the calculated volume, we will have leakage. For these reasons, if there were to be a machine with 5% volume tolerance, we will always overshoot and set up the machine to apply 105% of our desired volume. This ensures that there won't be any air trapped in the TIM.

The height of B2 will be higher than the TIM. When we compare heights of B1 (h1), TIM (h2), and B2 (h3), it will look like this: h1<h2<h3. When we are closing our application with a heat-sink or heat spreader, we will first hit B2. At that time, this barrier is not cured yet, so it can be squished down. Next, our heat-sink or heat spreader will hit our TIM (liquid metal or LMP) and it will squeeze out any extra material, which will then make contact with B1. Since that barrier is already cured, it will be solid and prevent any further movement of the heat-sink or heat spreader. After that, the whole application will go through a recommended curing process for B2 (both barriers can be made with the same material, but they can also be made with different materials). Very often, the material used for B2 will make mechanical bond between the substrate and heat-sink or heat spreader. It is very important to highlight that there should not be any components between those barriers. If there are some components, they should be covered with insulation layer. Sometimes barrier materials will also play a roll of insulation layer. In Fig. 8 below, you can see how a double barrier system works with liquid metal TIM.



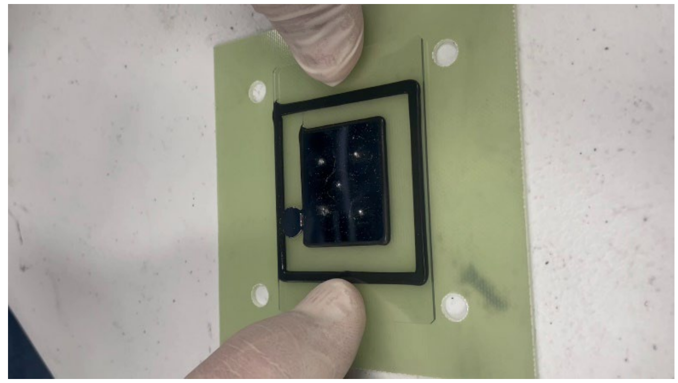


**Figure 8.** Double barrier system for liquid metal TIM.

## III. Liquid Metal Pastes

Liquid metal paste is a material made from well-known liquid metal alloys like GaIn and GaInSn, by a very specific process and with a certain additive. This material retains all the good properties of for liquid metal—good thermal conductivity, low interfacial resistance, and low bondline thickness—but it will have higher viscosity than liquid metal (Fig. 9).

**Figure 9.** Liquid metal paste.

Even though LMPs will have very good thermal conductivity, it will be not as good as the thermal conductivity of liquid metals. The biggest advantage of LMPs over liquid metals would be their mechanical properties. Thanks to their high viscosity, these materials can survive more drop shock tests than liquid metals, without any leakage. Also, LMPs will spread isotopically (in all directions) while liquid metals would squirt in different directions (Fig. 10 and 11).

**Figure 10.** Spreading of liquid metals when compressed with the glass slide.

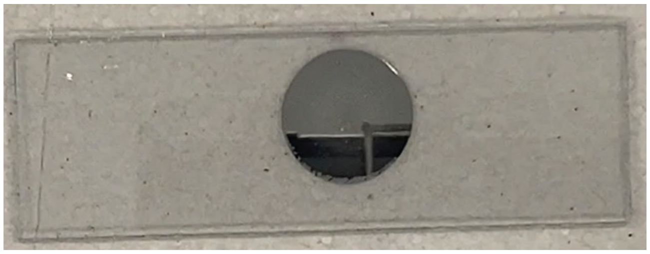


**Figure 11.** A dot of LMP will form almost perfect circle when it's compressed with the glass slide.

This characteristic of LMPs can be very helpful in HVP. Material can be applied in a certain pattern and when the application is closed with a heat-sink or heat spreader, LMP will spread evenly and cover whole area of the heat source (Fig. 12).

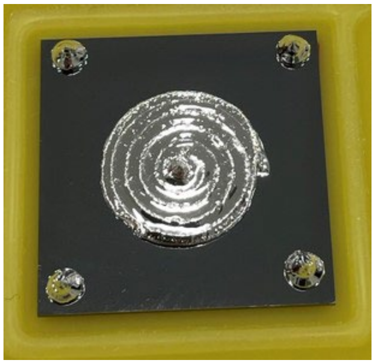


**Figure 12.** LMPs can be applied in HVP in certain patterns.

When we talk about recommended process for HVP for LMPs, dispensing and jetting would be the best options. Printing is possible option, but it is very challenging since LMP doesn't contain flux. Regular soldering paste will roll over the stencil when it's pushed by a squeegee. On the other hand, LMP will slide on the stencil, and it will take at least two swipes until the material can be pushed through the apertures. It would also be very hard to keep uniform BLT of a LMP TIM. Fig. 13-15 show how LMP can be applied by a dispensing process with double barrier system for leakage prevention.

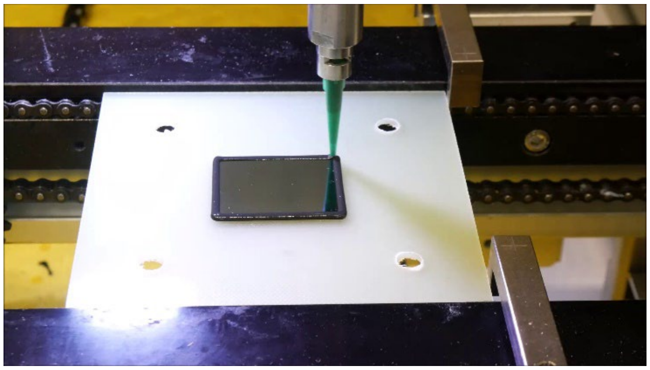


**Figure 13.** First barrier applied at the edge of the die.

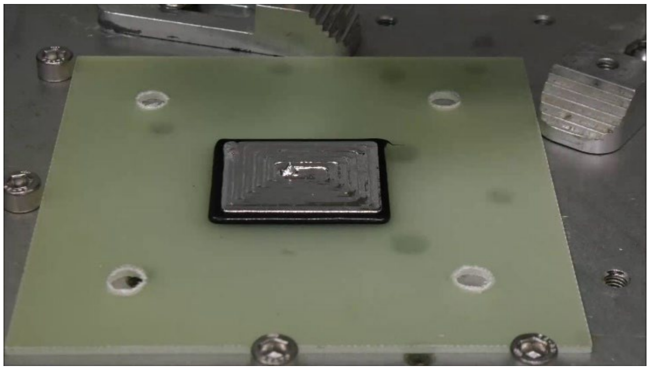


**Figure 14.** LMP applied by dispensing process on the back side of the die.

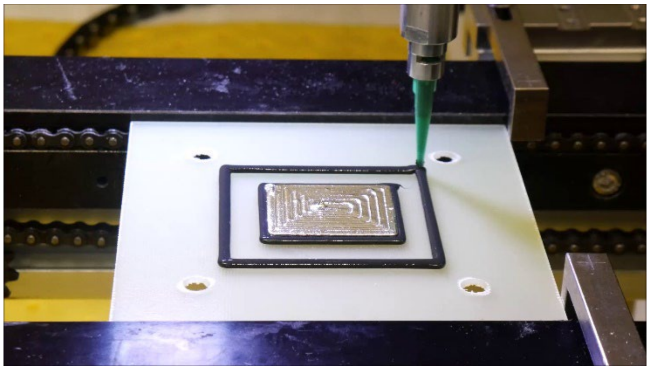


**Figure 15.** Second barrier applied by dispensing process.

As mentioned previously, B1 has been applied and then cured. After that, the LMP and B2 were applied. Jetting will be very similar to dispensing process. Fig. 16 shows how LMP can be applied by jetting with a double barrier system for leakage prevention.

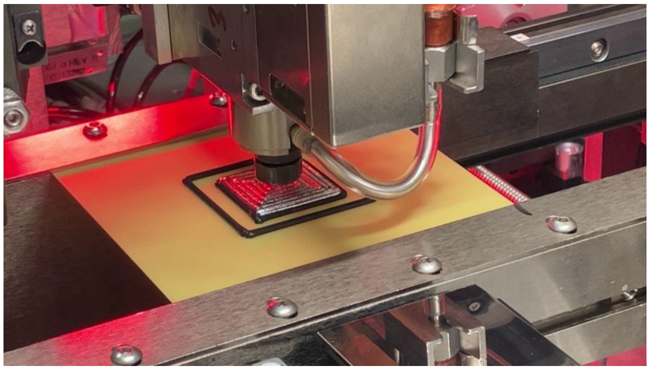


**Figure 16.** LMP jetting with double barrier system.

Similar to dispensing machines, jetting machines can also have multiple heads in one machine. In this case, a jetting machine with two heads was used, so LMP and B2 were both applied in the single machine. In Fig.17, we can see how LMP will spread when it's compressed with the glass slide.

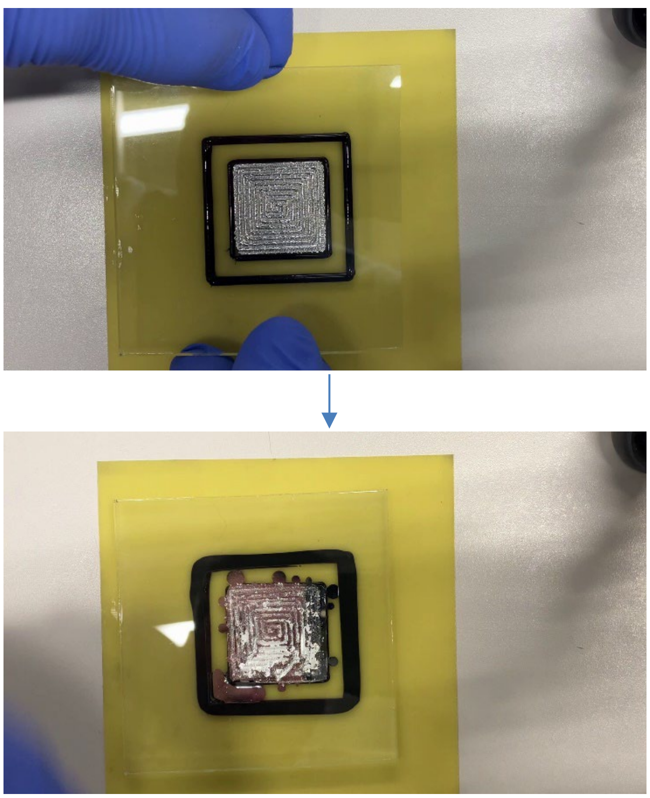


**Figure 17.** Spreading of jetted LMP with double barrier system for leakage prevention.

## IV. Conclusion

Even though the thermal conductivity of LMPs cannot reach the level of LMs, there will be some applications where their mechanical properties will play a big roll. Overall, the thermal conductivity of both materials will be higher than the thermal conductivity of standard thermal pastes or phase change materials (PCMs). Besides that, thermal pastes and PCMs must be applied in a very thin layer in order to have a good thermal performance, and that procedure is very challenging. On the other hand, with LMs and LMPs thermal resistance doesn't change dramatically with BLT. Fig. 18 shows how thermal resistance will change with BLT for liquid metal, LMP, and two standard PCMs.

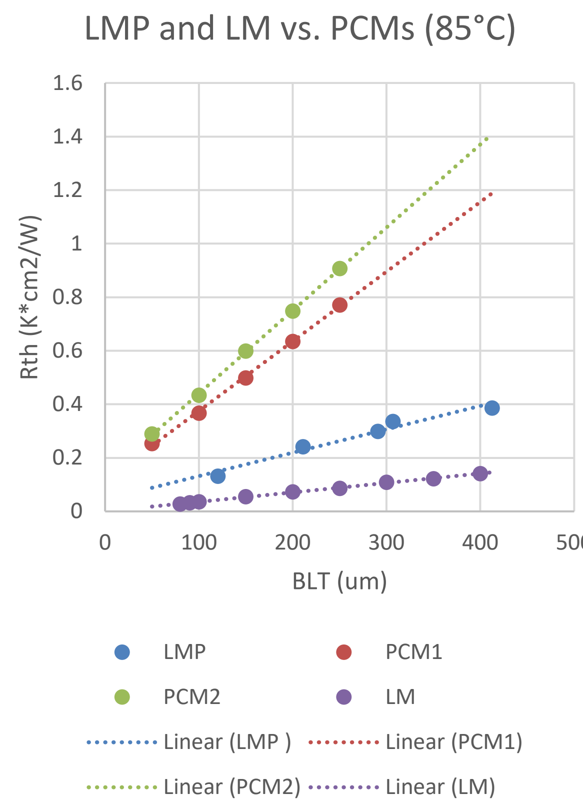



**Figure 18.** Thermal resistance vs. BLT for LM, LMP and 2 standard PCMs.

In the end, we can say that metal TIMs will very often outperform any other type of thermal interface due to their high thermal conductivity. LMPs with their unique properties would be a good option for some very challenging applications.

## Acknowledgment

The author would like to thank Jon Major and Dr. Ricky McDonough for their assistance with the research for this paper.

## References

[1] M. Lazić, "Liquid Metal TIMs," SEMI-Therm 2019.
[2] M. Lazić, "Solid Liquid Hybrids," APEX 2021.
[3] M. Lazić, A. Mackie, T. Jensen, B. Jarrett, B. Rolewicz, "Solid Liquid Hybrid TIMs—Part II, The Power of m2TIMs™," APEX 2022.
[4] H. M. Huang, C. Lee, H. Xi, Y. Liu, L. Zeng, L. Shen, "Thermal Management Using Phase Change Materials," Chip Scale Review, November–December 2014.
[5] R. N. Jarrett, J. P. Ross, and R. Berntson, "Full Metal TIMs."
[6] D. Socha, C. Hotvedt, J. Hisert, T. Jensen, B. Jarrett, and H. Zhang, "Emerging Applications for Non-Hg Room Temperature Liquid Metal Alloys," ASM International 2019.
[7] IdTechEx, "Thermal Interface Materials 2021–2031: Technologies, Markets and Opportunities."
[8] M. D. Dickey, M. Lazić, M. H. Vong, J. Ma, L. Kresge, C. LaBarbera, *et al*., "Liquid Metal Enabled Soft and Stretchable Electronics," APEX 2022.
[9] M. Lazić, Dr. R. McDonough, "High-Performance Phase Change Metal TIMs," APEX 2023