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Mind the (Air) Gap – The Key to a Successful TIM

If you have ever travelled in London using their subway system, called the Tube, you will be familiar with the warning of "Mind the Gap". This warning alerts riders to carefully board or exit a subway car because there is typically a space, or gap, between the railcar and the platform. Getting your foot caught in that gap will lead to unpleasant consequences.

It turns out that for Thermal Interface Material (TIM) used in microelectronics, there is a similar gap danger – in this case air is the culprit.

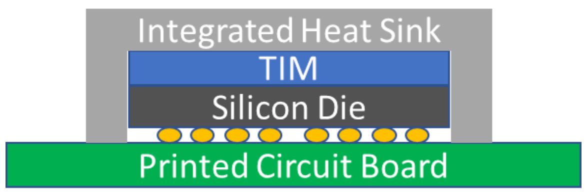

Figure 1: Simplified sketch of BGA Package

A simplified illustration of TIM usage in an integrated circuit application is shown in **Figure 1**. In this simplified view of the system, the integrated heat sink (IHS), constructed from high thermally conductive metal, will come into thermal equilibrium with the surrounding, or ambient temperature. The silicon die, when circuitry is active, will produce significant heat. For example, modern microprocessors used in datacenters commonly generate power densities on the order of 100 watts per square centimeter ($100W/cm^2$). The challenge is to get the heat away from the silicon die while minimizing the increase in die temperature, referred to as *junction temperature*.

The job of the TIM is to provide an efficient conduit for this heat to escape the die. The ability to minimize elevation of junction temperature is critical, as a semiconductor's useful lifetime is inversely related to its junction temperature[i]. This phenomenon is often modeled as a thermal resistance, Θ_{ja}, which has units of Kelvin per watt (K/W). When the ambient temperature is controlled, and the power dissipation known, the silicon junction temperature is easily calculated:

$$\text{Temp\_junction} = \text{Temp\_ambient} + (\text{Power} * \Theta_{ja})$$

The complexity of this job becomes apparent when we consider a microscopic view of the TIM interface, as illustrated in **Figure 2**. Rather than having a smooth interface, real materials consist of rough surfaces creating gaps that are filled by air. Since air is a poor conductor of heat, these air gaps place a limit on the thermal performance through a mechanism known as [Kapitza resistance][ii].

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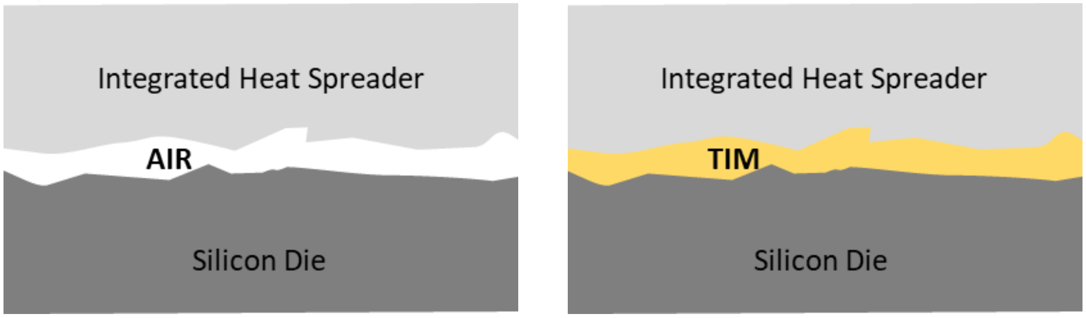

Figure 2: Air gaps created due to surface roughness and those gaps filled with a TIM

TIM-based solutions attempt to solve this problem by displacing air and filling the gap with a high thermally conductive material. An effective TIM can improve the thermal performance of an interface by over an order of magnitude when compared to an air gap. However, as we examine the details of this problem, the challenge becomes more daunting.

One cannot simply select the TIM material with the highest thermal conductivity and be done with it. In fact, poor thermal contact resistance is a reason why materials with extremely high thermal conductivity, such as carbon nanotubes (CNT), have demonstrated poor overall thermal resistance in practice[iii].

In addition to having good thermal conductivity, a TIM must also easily conform to non-uniform surface profiles, establish low contact thermal resistance with silicon and metal, tolerate significant expansion and compression as a device heats and cools throughout its operating cycle, and resist the absorption of moisture.

Developing a material that satisfies all the above requirements, as well as being compatible with high-volume manufacturing (HVM) workflows, is a challenge. It requires finding a base polymer that meets the reliability requirements such as thermal stability, low elastic modulus, and good wetting properties. This polymer matrix needs to be filled with an additive that increases thermal conductivity without compromising the desired mechanical characteristics. Commonly used additives, such as silver, are solids at the temperature of operation. Because these solids are rigid, they compromise the ability of the TIM to conform to microscopic surface imperfections. Lastly, the final TIM formulation must have a stable shelf-life, useful pot life, and maintain its integrity over the stress and lifetime of a commercial device. Designing such a material requires combined attention to mechanical engineering, polymer science, composites engineering, and scalable manufacturing.

Arieca's TIMbber™, which is a proprietary Liquid Metal Embedded Elastomer (LMEE) formulation, meets the above mechanical requirements while maintaining excellent thermal resistance, as shown in **Figure 3**.

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Based on a liquid filler system, TIMbber™ overcomes the inherent limitations of TIM material systems based on rigid fillers, resulting in excellent conformity to rough surfaces. Dispensed in emulsion form and cured-in-place, it can form bond line thicknesses (BLT) on the order of 20 microns, maintains its structural integrity in the face of expansion and compression due to mismatches in coefficients of thermal expansion, and is compatible with the semiconductor industry's HVM practices.

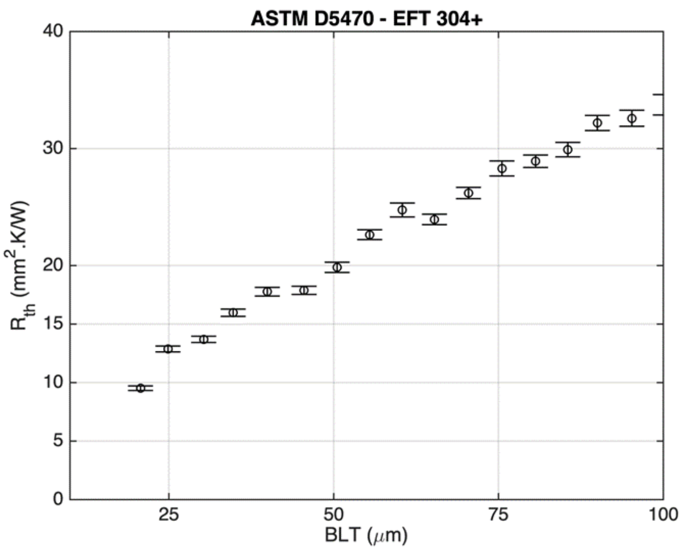

Figure 3: ASTM D5470 Measurements of TIMbber™ Thermal Resistance

In the world of high-performance semiconductors, something as benign as an air gap can create a bottleneck in overall system performance. An air gap can have as severe an impact on a semiconductor's performance as Martin Keown did to Ruud van Nistelrooy's career. Selecting the correct TIM for your application is not straight forward. There are many things to look out for – but above all, mind the gap!

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[i] www.ti.com: Calculating Useful Lifetimes of Embedded Processors
[ii] https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa2-706186
[iii] M. Springborn, etal."Transient thermal management by using double-sided assembling, thermo-electric cooling and phase-change based thermal buffer structures: Design, technology and application" in 21st International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Paris, France, 2015.