Thermal management using phase change materials

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While a variety of thermal management solutions are available in the marketplace, phase change material (PCM) technology is growing in popularity because of its ability to take thermal management to the next level in terms of device performance, long-term reliability and processing efficiency.

The use of PCM technology is critical because heat generation is a growing concern as more power and speed is packed into smaller devices across applications – from mobile smart phones and tablets to CPUs, gaming consoles, video graphics array (VGA) display cards, telecom products and servers. This trend is requiring integrated circuits (ICs) to perform at significantly higher power densities under extremely tight real estate and package constraints.

As power increases, so does heat, which is why thermal management is becoming an increasingly vital step in the design process. Because building larger heat sinks isn't possible given shrinking architectures, manufacturers are applying more resources toward the study and selection of thermal interface materials (TIMs) that manage excess heat, reduce operating temperatures (and thereby improve speed) and ensure long-term reliability.

Various classes of TIMs provide their own set of benefits and trade-offs. Greases, for example, may offer excellent thermal performance, but ongoing reliability is a challenge in high heat situations because of degradation issues. Advances in PCM technology are overcoming such trade-offs, making it an attractive and proven thermal management solution in challenging applications.

TIM types

In a typical high-powered IC application, the thermal material applied at the interfaces between chip, heat spreader and heat sink is critical to long-term device performance. The TIM needs to reliably fill air gaps and surface irregularities, increasing heat transfer to the heat sink so the device can run cooler. As shown in Figure 1, types of TIMs include: 1) TIM-1 – which is applied between the IC and heat spreader; 2) TIM-2 – which is applied between the heat spreader and heat sink; and 3) TIM 1.5 – which is becoming more common. In this design, there is no heat spreader and the TIM 1.5 is applied between the IC and heat sink.

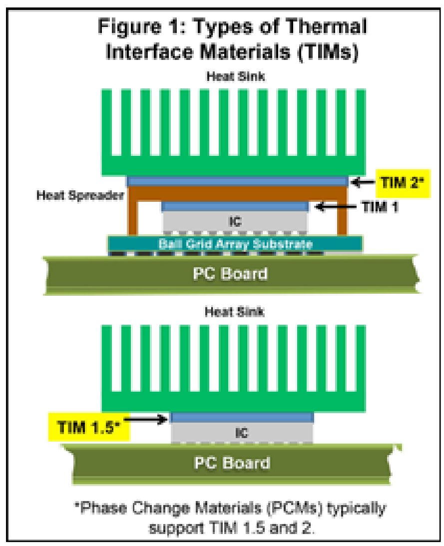


Figure 1: Types of thermal interface materials (TIMs).

TIM properties

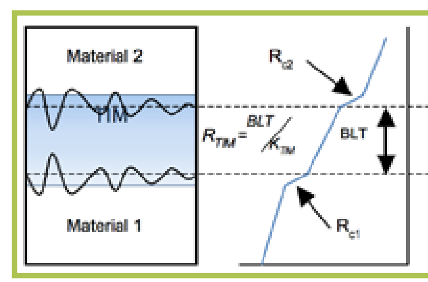
Key properties critical to evaluating the performance of TIMs include:

Low thermal impedance. The true test of performance is thermal impedance (TI), which measures resistance in units of °C-cm^2/W. This measure shows how a material performs in the actual application, accounting not only for its bulk thermal conductivity, but also for its performance at the interfaces where thermal contact resistance occurs (e.g., heat spreader and heat sink). While high bulk conductivity is important, it is not exclusive. While materials with a lower TI should be the focus as they provide the best heat transfer, testing in-system will determine TIM performance. TI is affected by the properties described in the following formula:

$$TI_T = BLT/K + R_C$$

where:

TI_T = Total thermal impedance
BLT = Bond line thickness of the TIM
K = Bulk thermal conductivity of the TIM
R_C = Thermal contact resistance at the interfaces (see inset)



inset

High bulk thermal conductivity. A higher bulk thermal conductivity indicates a better heat transfer rate through the material itself. Measured in W/m-K, it is an intrinsic property that indicates the "potential" for heat transfer through the bond line of the TIM. While commonly listed in data sheets, it alone does not truly reflect the TIM's actual performance relative to surface interfaces and contact resistance.

High surface wetting and low thermal contact resistance. Achieving full surface wetting and contact at the interface is critical to minimizing contact resistance and maximizing heat transfer. The flexibility to penetrate varying degrees of surface roughness is critical. Lower viscosity is associated with higher wetting properties and can be measured by contact angle. A lower contact angle is an indication of excellent wetting.

Low bond line thickness. Bond lines well below 0.1mm are necessary for today's high-powered applications. Achieving thin bond lines while maintaining a stable polymer matrix (even under clamping pressures) reduces the thermal resistance path, improves reliability, and meets the needs for confined spaces. TIMs with a lower viscosity have the higher flowability needed for thinner bond lines.

High thermal stability (reliability) over time. Thermal stability is an important indicator of the long-term performance of a material. It is measured by assessing the performance of a TIM after accelerated life tests (ALTs). Such tests include temperature cycling, high-temperature bake, and highly accelerated stress tests (HASTs). TIMs that can withstand this abuse have a reduced risk of failure and can help define product life and end-use warranties.

Classes of TIMs

Several classes of TIMs are available in the marketplace, including thermal greases, PCMs, thermal adhesives and thermal gap pads. While this article focuses primarily on PCM performance, below is a high-level comparison of the benefits and limitations of each class:

Thermal greases. Typically silicone-based, greases are non-curing, conformable and reworkable. While they provide low thermal resistance, they can degrade, pump-out or dry out after repeated thermal (on/off) cycles, causing failure and potential contamination of adjacent components. They also can be messy and difficult to apply because of its paste form factor, requiring high-precision dispensing equipment. Furthermore, mechanical clamping is required.

PCMs. PCMs combine the advantages of a thermal gap pad along with the thermal performance of a grease. This material transforms from a solid state to a liquid or gel state as the temperature reaches its phase change or melt temperature. Like greases, PCMs provide low thermal resistance and are non-curing and conformable, but do not have bleeding, dry-out and other degradation issues. PCMs, which are typically available in a film form factor but also in a paste format, are easy to apply. They can be coated directly onto release liners and cut into pads at various thicknesses to better meet design and heat requirements. Mechanical clamping is required, and they are reworkable.

Thermal adhesives. These are one- or two-part cross-linkable materials based on epoxies or silicones. They provide low thermal resistance and are known for their structural support. While this can eliminate the need for mechanical clamps, cure time is required and they are not reworkable.

Thermal gap pads. Pre-cured thermal pads are typically thicker (>1mm) than other TIMs, and are designed to have good compression properties. When pressure is applied, the material conforms to the surface, filling gaps and irregularities. Gap pads are reworkable, and may require a carrier film such as silicone or fiberglass to maintain their thickness. They usually cannot deliver the same level of thermal performance as the TIMs described above. Mechanical clamping or screws are typically required.

As noted, each class of TIM has limitations. While PCMs, for example, require mechanical clamping, this is significantly outweighed by their advantages in long-term performance and reliability.

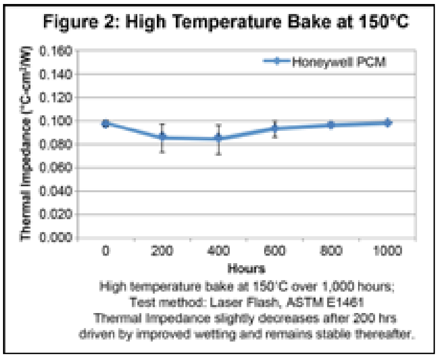


Figure 2: High-temperature bake performance of PCMs.

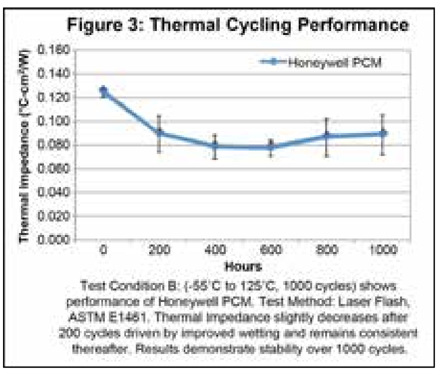


Figure 3: Thermal cycling performance of PCMs.

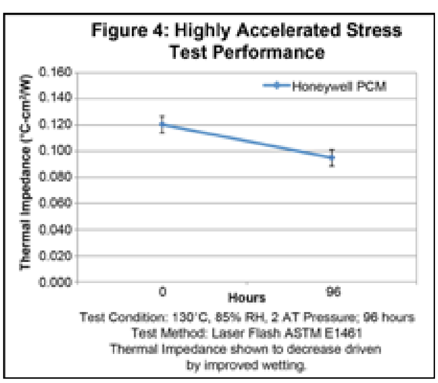


Figure 4: PCM performance in highly accelerated stress tests.

PCM performance

As shown in **Figures 2-4**, PCMs typically deliver a low thermal impedance (TI) (<0.1°Ccm^2/W) and high thermal stability over time, demonstrating excellent long-term wetting and reliability. This is true despite repeated thermal cycles, elevated temperatures and extended harsh test conditions. Specifically: 1) **Figure 2** shows the outstanding performance of a PCM in a high-temperature bake test over 1,000 hours; 2) **Figure 3** demonstrates the excellent stability of a PCM over 1,000 thermal cycles with no degradation; **Figure 4** reveals the ability of a PCM to perform under HASTs with no loss in performance. In addition, **Figure 5** shows the ability of a PCM to achieve a bond line thickness of <0.03mm, further reducing TI.

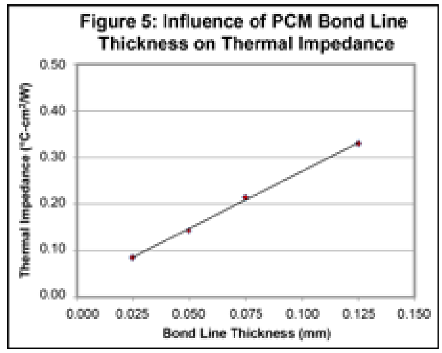


Figure 5: Influence of PCM bond line thickness on thermal impedance.

Impact of polymer structure

PCMs meet all of the critical TIM properties stated above: low thermal impedance, excellent wetting, low contact resistance, low BLTs and high thermal stability. This is largely because of their unique polymer structure and phase-change capability.

Most PCMs contain wax-based polymers, transforming from solid state to a liquid or gel state as the temperature increases during device operation. The melting process, which is reversible, occurs when temperatures exceed the melt temperature – typically in the 45°C to 70°C range. **Figure 6** shows the transition from a solid to liquid state and the impact of temperature on viscosity. Increasing temperatures result in low viscosity, which not only delivers high wetting at the interfaces but also excellent flowability for ease of application.

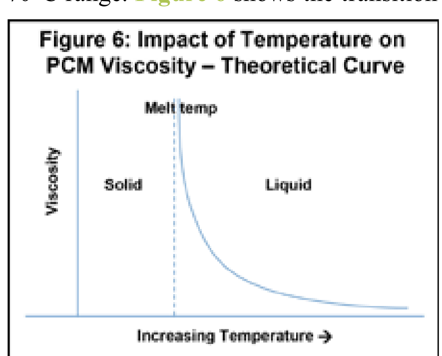


Figure 6: Impact of temperature on PCM viscosity.

Polymer structure and molecular chains play an important role in performance, as illustrated in **Figure 7**. PCMs are higher molecular weight polymers in the 5,000-7,000mw range, comprised of longer polymer chains than those found in greases. Long chains enable a stable and consistent filler dispersion and polymer matrix, improving thermal conductivity and minimizing migration. In addition, as the temperature decreases, the PCM solidifies, maintaining the polymer matrix integrity and thereby, long-term reliability.

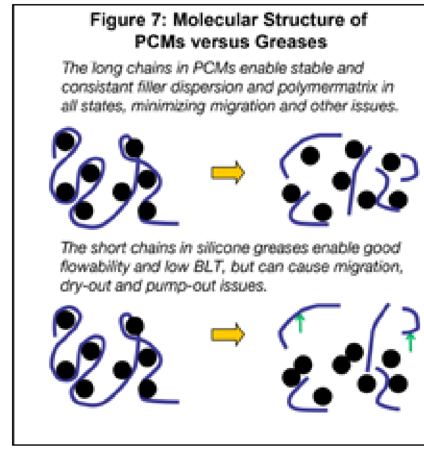


Figure 7: Molecular structure of PCMs vs. greases.

In comparison, silicone greases are comprised of non-curable silicone with short-chains in the matrix. This ensures good flowability and low BLT, which is a key contributor to their thermal performance. However, as mentioned, the easy migration of silicone may cause bleeding, pump-out and dry-out issues over time.

As with most TIMs, PCMs include a filler material responsible for conducting heat. Filler loading (type and particle size) affect viscosity and flowability, and are chosen to provide the best balance. Common PCM fillers include metal particles, such as silver and aluminum, and ceramic powders, such as alumina and zinc oxide.

An additional important property inherent to PCMs is latent heat of fusion – the storage and release of energy as they change states. This enables thermal absorption and provides a valuable temperature buffer, regulating the device temperature particularly during sudden bursts of power and temperature spikes.

PCM growth and versatility

PCM growth in electronics is largely driven by the material's ability to meet demand for higher thermal performance, long-term reliability and cost-effectiveness, including productivity improvements. For example, PCMs: 1) Can be dropped into the current production environment without new equipment investments; 2) Are easy to apply, improving yields while reducing rejects and waste; 3) Can help reduce product failures and returns; and 4) Are easy to rework, reducing assembly failure.

In addition, PCMs have the versatility to support the different priorities of multiple applications. Examples include: servers, telecom equipment, notebooks, tablets, smart phones, video graphics arrays (VGAs), high-brightness light emitting diodes (HBLEDs), as well as compact video recording devices.

Summary

Thermal management is a growing concern as more power and speed are packed into smaller devices across applications. As heat increases, so does the need to dissipate it. PCMs are gaining widespread acceptance as a TIM that can take the heat. They can deliver similar, if not better, thermal performance than traditional TIMs but with greater long-term reliability, improved application ease, and minimal risk of migration and pump-out. These and other benefits can also help manufacturers improve productivity – a welcome bonus.

PCMs are expected to play a pivotal role in the future of electronics and are already proving their value in a variety of demanding applications. Manufacturers will see continued innovations as these materials not only respond to, but also enable, advances in the electronics industry.

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