Advanced Polymer Formulations for Thermal Management of Electronic Devices

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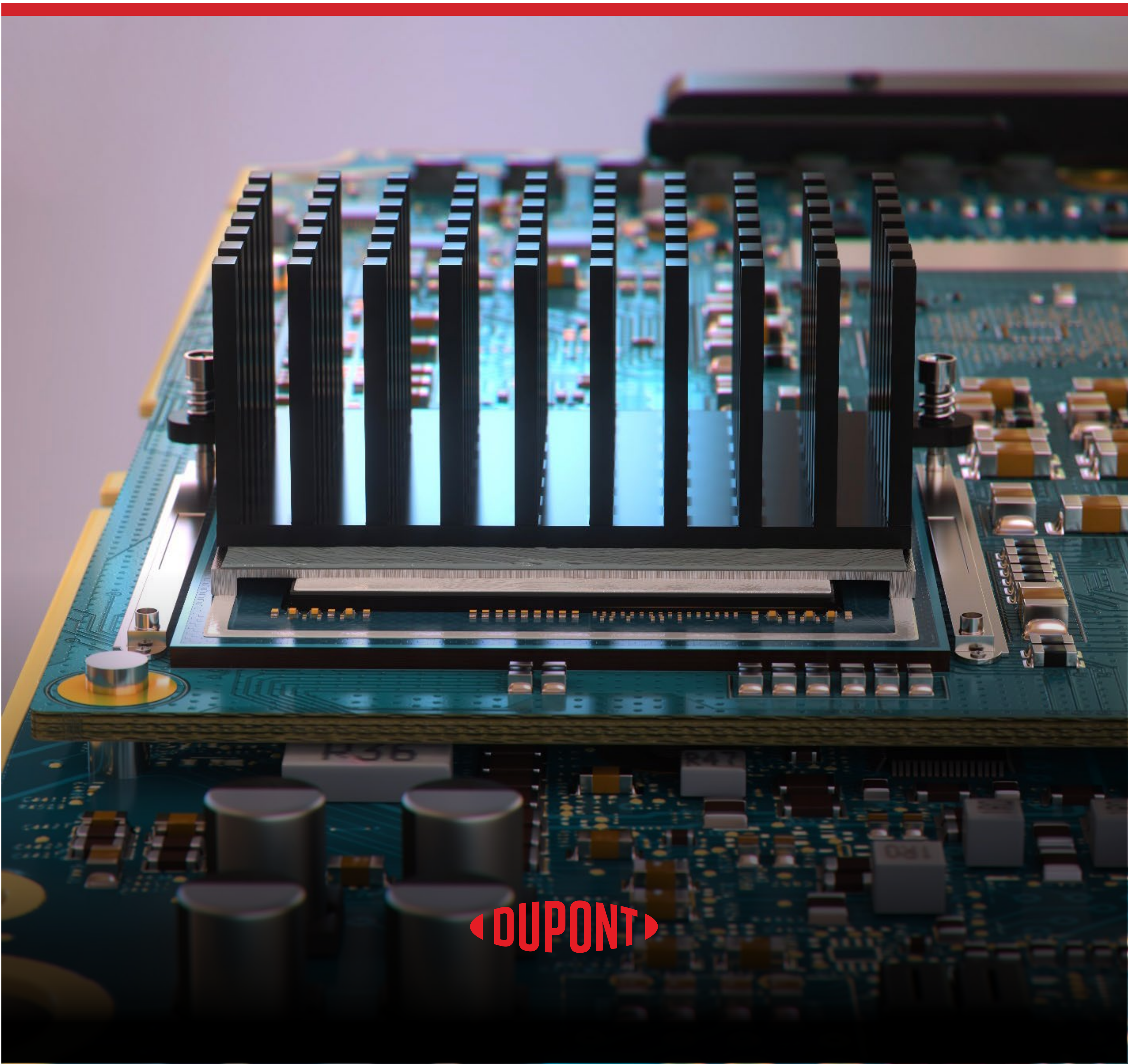

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Abstract

Overheating is the number one cause of electronic component failure and requires aggressive thermal management strategies. That's why thermal interface materials (TIMs) have become ubiquitous in today's electronic assemblies, working to dissipate heat from heat-sensitive components, improve device reliability and prevent premature failure.

There are two main categories of thermal interface materials, TIM1, and TIM2. When used together they create a comprehensive thermal management solution at both the chip and semiconductor package level.

TIM1 materials remove heat at the chip level, creating a thermal conduction pathway from the heat generating chip to its metallic lid. As the first line of defense against overheating, TIM1 materials are vital for long term reliability. TIM1 materials are formulated to meet rigorous requirements. They must withstand temperatures up to 150°C (in reliability cycling), effectively wet adjoining surfaces and mitigate heat induced mechanical stresses caused by CTE (Coefficient of Thermal Expansion) mismatches. CTE is a material property that describes the extent to which a material expands and contracts due to changes in temperature.

TIM2 materials remove heat at the package level, creating a thermal conduction pathway from the exterior of the semiconductor package to a heatsink, heat pipe, or other heat spreader. TIM2 materials are the second line of defense against overheating and must withstand temperatures up to 120°C for reliability aging tests.

In use, TIM1 and TIM2 materials will see a range of operating temperatures, dictated by the type of chip they are connected with. In automotive MOSFET or IGBT chips, operation temperatures can run well over 120°C at the die interface. Operating temperatures are cooler for data center chip packages, and even cooler for portable electronic devices.

Thermal cycling and surface adhesion are major challenges that affect long term reliability and performance of TIM materials. Raw materials and fillers must be carefully selected and formulated to avoid embrittlement and delamination when exposed to thermal cycling. And they must be able to retain their conformability in extreme environments for the lifespan of the device, taking on the contours of rough adjoining surfaces to fill air gaps and voids.

Introduction

All electronic components generate excess heat. As electronic devices become smaller, faster, and more functional, they generate even more heat in smaller more confined spaces, which can lead to serious reliability issues if maximum operating temperatures are exceeded. This phenomenon is referred to as increased heat flux (measured in Watts/cm2).

Heat has rapidly become a major reliability issue in the electronics industry, making thermally conductive materials an essential part of solving the problem of heat related failures, which is why the TIM market is booming. Grand View Research estimated the global TIM market to be $1.84 billion in 2021 and forecasted the market to expand at a compound annual growth rate (CAGR) of 11.4% between 2022 and 2030. That means the market is projected to reach $4.86 billion by 2030.

DuPont Expands Capabilities in Thermal Interface Materials

DuPont's Silicon Valley Technology Center in Sunnyvale, California broadened its capabilities in material science and advanced polymers for thermal management through the merger with Dow in 2017 (gaining parts of the thermal portfolio from Dow Corning), and the acquisition of Laird Performance Materials in 2021. The combined entities bring collective strengths in chemistry, innovation, and engineering to solve the electronics industry's ever-evolving heat management challenges while supporting industry trends in high-performance computing, 5G telecommunications, smart appliances, miniaturized electronic devices, artificial intelligence, and smart, electric, and autonomous vehicles.

Dow Corning's extensive experience with TIM1 type materials and Laird Performance Materials' comprehensive expertise in TIM2 type materials, has moved DuPont into the electronics market as a major player in both TIM1 and TIM2 type thermal interface materials, broadening their market reach and abilities in thermal management applications.

TIM1 Materials – First Line of Defense for Chips

TIM1 type materials are used as the first line of defense to prevent overheating and improve reliability of heat sensitive components such as IC chips. TIM1 materials are typically placed inside the semiconductor package, between the heat generating chip/or die and a heat spreading metallic lid, making contact with both for more direct heat dissipation. A typical TIM1 assembly configuration is shown in Figure 1.

Increasingly, silicone is being used as the base material of choice for TIM1 type materials, and formulations functionalized chemistries that promote thermal conductivity and surface wetting. Wetting refers to the ease with which a material bonds with a given substrate. A variety of forces (ionic, static, polar, van der Waals etc.) act to create chemical linkages and improve molecular attraction to ensure optimal wetting, and therefore reduced thermal resistance is accomplished.

DuPont's advanced silicone based TIM1 formulations have unique properties. When cured, they maintain a gel-like consistency, which is ideal for TIM1 applications where there can be a significant amount of heat induced warpage. Warpage, a major cause of heat-related reliability issues, is caused by large CTE (Coefficient of Thermal Expansion) mismatches between the heat generating component and the metallic heat spreading lid. DuPont's TIM1 gel-like materials maintain a low modulus of elasticity, allowing them to absorb warpage-induced mechanical stresses without transferring them to the chip.

TIM2 Materials – Second Line of Defense for Chips

For high heat generating components such as TOs, FPGAs, MOSFETs and IGBTs, heat sinks, heat pipes, fans and heat spreaders are added on the outside of the semiconductor package. TIM2 materials are utilized in this configuration as the second line of defense to further dissipate heat, prevent overheating, and

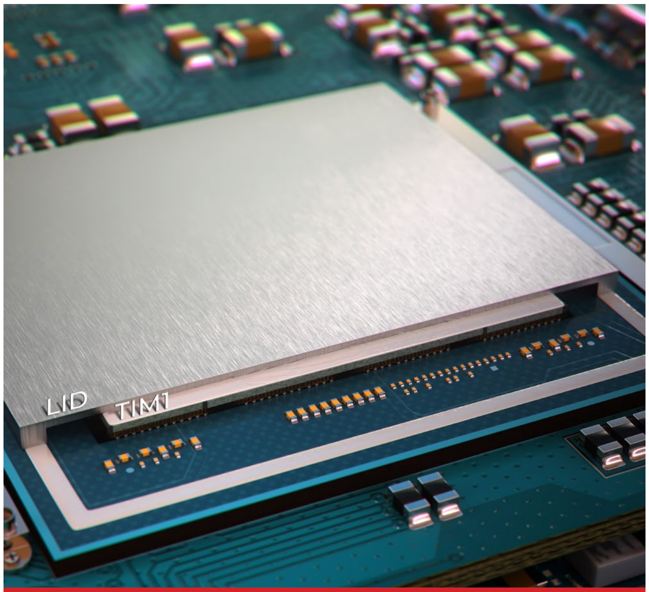

Figure 1 – TIM1 Material Configuration

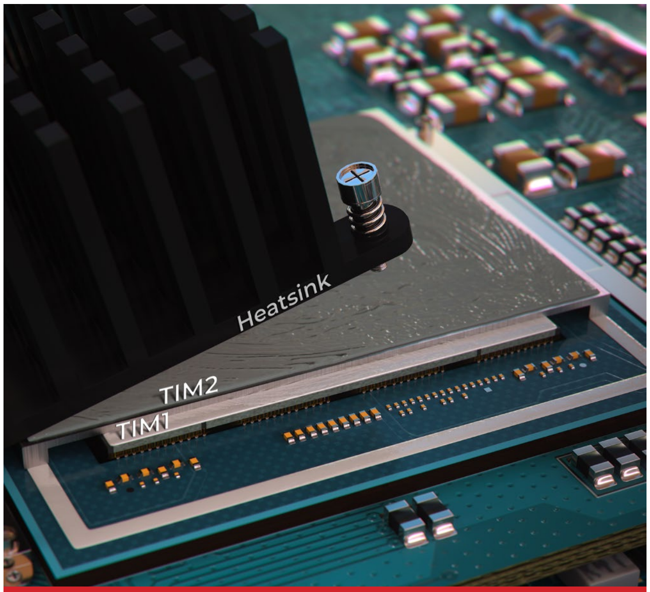

Figure 2 – TIM2 and TIM1 Material Configuration

improve reliability. As shown in Figure 2, TIM2 materials are typically placed between the outside of the semiconductor package and a heatsink. When coupled with TIM1 products, TIM2 materials provide extra heat dissipation capability.

DuPont's broad TIM2 portfolio includes Laird's liquid gap fillers, gap pads, thermally conductive tapes, sheets and adhesive, phase change materials, thermal greases, and thermally conductive/electrically insulating materials as well as DuPont's formulated TIM2 for automotive applications between battery packs and heat sinks.

Performance Requirements of TIM1 and TIM2 Materials

From a technology perspective, TIM1 reliability and performance requirements are much more demanding than that of TIM2, requiring higher performance fillers and formulations.

TIM1 materials must withstand extreme temperature cycling from -40°C to 150°C. Whereas the functional upper limit for temperature cycling TIM2 materials is typically closer to 120°C. While this 30°C difference in the upper temperature limit may not seem like much, it significantly eases the formulation requirements, allowing for more variability in base and filler material selections. Certain epoxies or other thermoplastic materials that might otherwise be contenders for TIM1 applications cannot withstand temperatures of 150°C without hardening and delaminating, resulting in thermal failure.

For this reason, most TIM1 materials are silicone-based chemistries to meet the 150°C upper limit and must also utilize surface treatments to functionalize the thermally conductive filler particles to endure extreme temperatures over time without becoming embrittled, changing its gel-like characteristics, and inducing mechanical stresses due to high CTE mismatch.

Temperature Cycling and TIM Reliability

Understanding the relationship between CTE mismatch and the end use environment is important for designing reliable TIM assemblies. Extreme temperature variations can induce significant mechanical stresses due to CTE mismatch between adjoining surfaces, which can lead to delamination of the TIM material.

DuPont thermal management materials are designed to withstand high-temperature conditions experienced by today's advanced electronic devices. DuPont formulations are optimized by selecting the right raw polymer materials and fillers for the job and are validated through rigorous environmental testing.

Interfacial Thermal Resistance - A Major Challenge for Heat Transfer

Heat transfer performance of both TIM1 and TIM2 materials is strongly influenced by the roughness of the surfaces on which they are applied. Surface

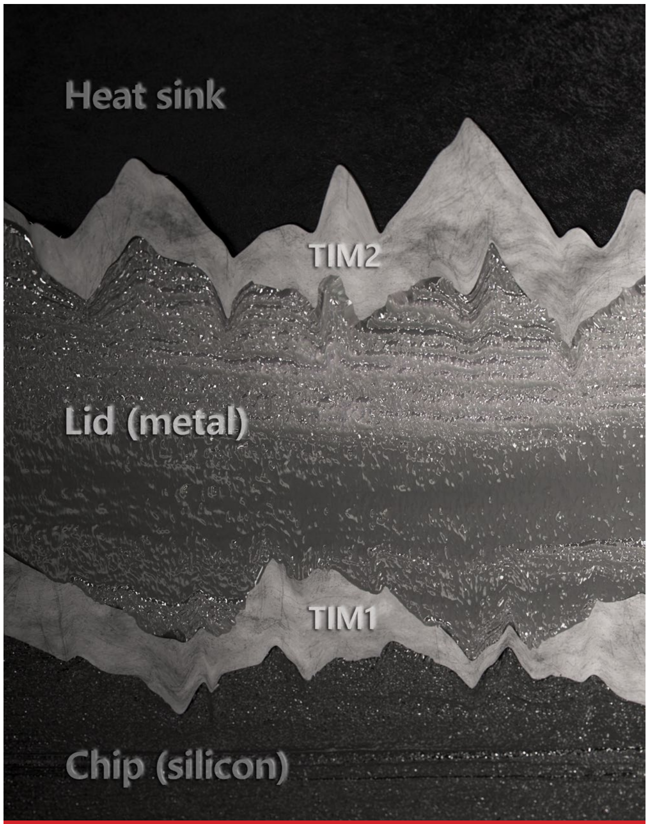

Figure 3 – Surface Roughness

roughness imperfections, like those illustrated in Figure 3, impede heat transfer by introducing microscopic air pockets which act as insulators. Small peaks and valleys on rough surfaces entrap air and increase thermal resistance. To transfer heat efficiently, TIM materials must be soft and compliant enough to fill air gaps and voids.

For this reason, most TIM1 materials are designed as dispensable gels that flow and wet adjoining surfaces without introducing compressive stresses. Whereas TIM2 materials are designed to be malleable and deform under compressive stress to fill voids.

The Mechanics of Thermal Performance

A common data point on a material's technical data sheet (TDS) is thermal conductivity, k, which indicates the material's inherent ability to conduct heat. Thermal conductivity, k, is measured in Watts per meter Kelvin (W/mK).

It is important to note that a material's thermal conductivity value is only one part of a larger equation that predicts the ability of an assembly to conduct heat in real-world applications. The thickness of the thermally conductive material and surface irregularities on the adjoining surfaces also affect the ability of the assembly to conduct heat.

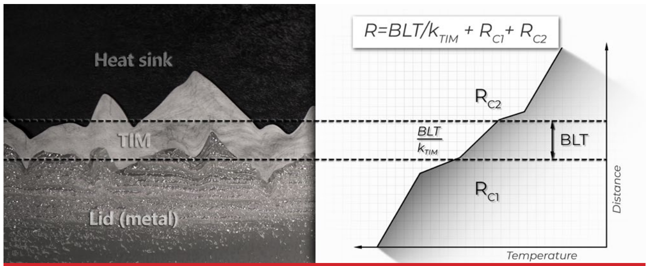

Figure 4 – Thermal Impedance $R_{th} = R_{TIM} + Rc1 + Rc2$.

Total thermal impedance, R_{th}, is a better predictor of thermal performance than the thermal conductivity of the TIM material alone. Thermal impedance, R_{th}, the sum of all thermal resistances through the assembly is measured in Kelvin per Watt (K/W).

A typical TIM assembly and the calculation of its thermal impedance is shown in Figure 4.

Where R_{TIM} is the bulk thermal resistance of the TIM material, R_{C1} and R_{C2} are thermal contact resistances between the TIM and adjoining surfaces.

An assembly that is better at conducting heat (higher k value) will have a lower R_{TIM} value and typically have a lower thermal impedance (lower R_{th} value) as well. However, exceptions to this are not unheard of. If a material has low R_{TIM}, but also has high contact resistance (it does not wet the adjoining surfaces effectively) it may actually have a higher R_{th} than a material with lower thermal conductivity, but very low contact resistance.

Thermal Conductivity (k) and Bond Line Thickness (BLT)

Optimizing bond line thickness (BLT) is one method of achieving lower thermal impedance and improving thermal performance of a TIM assembly. Selecting thinner TIM materials or applying compressive forces to TIM materials are common techniques used to minimize thickness and lower thermal impedance.

However, in TIM1 applications, where mechanical stresses are detrimental to the integrity of the die, adding too much pressure is avoided. DuPont's TIM1 formulations are designed to flow and wet a variety of surfaces, reduce contact resistance and achieve optimal bond line thickness while mitigating mechanical stresses.

In TIM2 applications where substrates are more durable, conformable gap pads and gap fillers are used under pressure which is typically applied through a mechanical clamping system. This mechanical pressure helps remove air gaps and voids and compresses

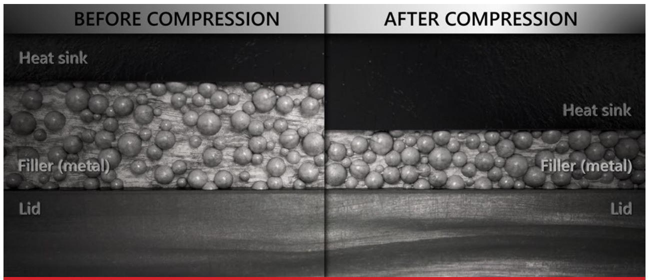

Figure 5 – TIM2 Gap Pad Compression for Optimal Thermal Impedance

conductive fillers particles closer together for improved thermal performance. The goal is to reach compression values that achieve the most advantageous thermal performance (typically 20 to 40 psi). Chemical formulations and fillers will affect the pressure necessary to achieve the minimum BLT. As shown in Figure 5, when optimized, pressure decreases overall thickness and creates intimate contact between the conductive filler particles, aligning them for the best possible thermal performance.

Technologies Driving the Future of Thermal Interface Materials

The ongoing movement toward the implementation of 5G telecommunications is increasing the demand for advanced TIM formulations. 5G antennas and devices generate more heat than their LTE predecessors due to 5G's mmWave frequencies. 5G Technology World reports that when designing 5G into a router or other fixed-access device, you encounter thermal issues to a greater "degree" than in products that use LTE for wireless communications, even though the energy-per-bit might be less than LTE. Some mobile phones on the market today are already capable of receiving and interpreting 5G signals. However, they can only do so for short burst before the hardware heats up, triggering the software to throttle back performance to protect the electronics and users from heat.

Trends in the automotive industry, like Advanced Driver Assistance Systems (ADAS) and electric vehicles (EVs) are also driving the need for new TIM materials. High-speed ADAS electronics that enable improved driver and pedestrian safety, and high-power electronics for EV battery charging and discharging create considerable amounts of heat. These, along with the potential for harsh temperature extremes in vehicle operating environments, creates a number of real thermal challenges for automotive electronics.

Conclusion

A comprehensive thermal management approach not only includes using the right TIM materials in combination with heat sinks, heat pipes, fans, and heat spreaders, but also includes a good thermal management strategy that starts during the design phase. Electronic systems can be designed to include thermal management at all levels (chip, package, PCB, and enclosure). Thermal simulations can be run before actual systems are manufactured to identify issues and optimize solutions. For example, PCBs can be designed with thermal vias and copper layers that help spread and dissipate heat at the board level. Solving heat related reliability issues is complex, involving many different variables that may require unique solutions for each specific application.

DuPont's Silicon Valley Technology Center, in the heart of Silicon Valley, is a hub for research and support with state-of-the-art engineering labs and customer meeting spaces that foster collaboration. DuPont Engineers can help you design a comprehensive heat management strategy on all levels, from chip to board. With computer modeling and advanced testing capabilities DuPont helps customers find the best solutions for their specific applications.

No matter what thermal challenge you face, DuPont's experts can address your specific needs and improve the reliability and performance of your electronic devices.