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FEATURE ARTICLE

# Advances in Thermal Interface Materials

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Overheating is the most critical problem in the computer industry, as it limits the further miniaturization, power, performance and reliability. An important way to alleviate this problem is to improve the thermal contact between the microprocessor and heat sink in the computer [1-5]. For this purpose, a material, known as a thermal interface material [6], is placed at the interface. In the case of a microprocessor with an integrated heat spreader, a thermal interface material is also needed for the interface between the die and the heat spreader.

Thermal interface materials can be in the form of a paste (known as a thermal paste, most commonly based on silicone) [7-13], flexible graphite [14-17], phase change materials [18-20], low melting alloys [21,22] and nanostructured carbon materials [10-13, 23-26]. A thermal paste should conform to the surface topography of the adjoining surfaces, because no surface is perfectly smooth and the valleys in the surface topography trap air, which is a thermal insulator.

Carbon black is a nanostructured carbon that is in the form of porous agglomerates of nanoparticles (size 30 nm [10-13]). Due to this structure, carbon black is highly conformable. In addition, the nanoparticles in carbon black can fill the microscopic valleys in the surface topography of the mating surfaces. Thus, in spite of the moderate thermal conductivity of carbon black, carbon black paste outperforms silver paste and solder as a thermal interface material [11].

The performance of a thermal interface material is enhanced by high conformability, high thermal conductivity and low thickness. For two mating surfaces that are flat and well aligned (i.e., parallel), the thickness of the thermal interface material is ideally such that the interface material is just enough to fill the valleys in the surface topography of the mating surfaces. However, the two surfaces may not be flat, i.e., there may be some curvature in one or both surfaces. Moreover, the two surfaces may not be well aligned, due to the way that the two surfaces are brought together. The more different are the areas of the two surfaces, the greater is the chance of misalignment during fastening. In the case where the surfaces are not flat or not well aligned, the gap between the surfaces can be substantial, at least locally. As a result, the thermal interface material needs to be relatively thick and is referred to as a gap-filling material.

Due to its relatively large thickness, a gap-filling material is commonly in the form of a sheet. An example is "flexible graphite" [14-17], which is a graphite sheet that is flexible and is resilient in the direction perpendicular to the sheet. The resiliency is made possible by the microstructure, which involves the mechanical interlocking of exfoliated graphite in the absence of a binder [27]. In general, a gap-filling material in the form of a sheet may be made more effective by coating both sides of the sheet with a thermal paste. This paper addresses gap-filling materials, in addition to thermal pastes.

Due to variability in the testing conditions (e.g., roughness and thermal conductivity of the mating surfaces) and methods (e.g., positions relative to the thermal interface of the temperature measurement), the relative performance of various thermal interface materials should be evaluated by using the same testing method and condition. Although the performance of various thermal interface materials has been reported, comparative evaluation has received little attention. Comparative evaluation is necessary for providing guidelines for the choice of a thermal interface material. In addition, it sheds light on the science of thermal interface materials.

Comparative evaluation [28] in this paper uses each of two methods. One method involves application-oriented testing by using a computer and measuring the temperature rise during computer operation. Another method involves scientific testing by using the Guarded Hot Plate Method, which involves measurement of the heat flux in the steady state (ASTM Method D5470) [13]. The latter method is more reliable scientifically, but the former method is commonly used in the electronic industry. This paper also provides comparison of the relative performance results obtained by using these two methods.

The application-oriented testing [28] used an Intel Pentium IV flip chip pin-grid array 2 (FC-PGA2) microprocessor (processor core frequency 1.7 GHz, system bus frequency 400 MHz, L2 cache size 256 Kbytes, core voltage 1.75 V) in a 478-pin package, which was integrated with a heat spreader (area = 960 $mm^2$) made of nickel coated copper with surface roughness 8 $\mu$m (Fig. 1). The pins, which were made of Au/Ni plated Kovar, were inserted in a socket that was made of a fiber-reinforced polymer (resin). The thermal interface material under evaluation was placed at the interface between the heat spreader (30 x 30 mm) and an aluminum heat sink (area of 88 x 64 mm and surface roughness 12-21 $\mu$m).

The maximum temperature difference across the interface between the microprocessor and heat sink surfaces, as obtained by two thermocouples (Type T), was measured as a function of time from the start of operation of the microprocessor [28]. The microprocessor temperature increased with time, causing the temperature difference between the two thermocouples to change with time. The temperature difference at a time of 5 min was used for the comparative study. The smaller is the temperature difference, the less is the thermal resistance and the better is the performance.

In the Guarded Hot Plate Method, the thermal contact conductance was measured between two 1 x 1 in (25 x 25 mm) copper surfaces of roughness 15 ìm that sandwiched a thermal interface material [28]. The pressure in the direction perpendicular to the plane of the thermal interface was controlled at 0.46 MPa (50 psi) by using a hydraulic press.

The thermal interface materials evaluated are listed in Table 1 [28], where FG denotes flexible graphite of thickness 0.13 mm and Al denotes aluminum foil (1145) of thickness 0.007 mm. Also evaluated were materials in the form of pastes, namely carbon black (1.25 vol.%) polyethylene-glycol (with 3 vol.% dissolved ethyl cellulose) paste [10,11], commercial "Arctic Silver 5" (polyol ester filled with micronized silver particles, together with smaller quantities of submicron particles of boron nitride, zinc oxide and aluminum oxide, such that all the conductive fillers together make up 88 wt.% of the paste, from Arctic Silver Inc., Visalia, CA) and commercial "Shin-Etsu X-23-7762" (aluminum particle filled silicone from Shin-Etsu MicroSi, Inc., Phoenix, AZ). Flexible graphite and

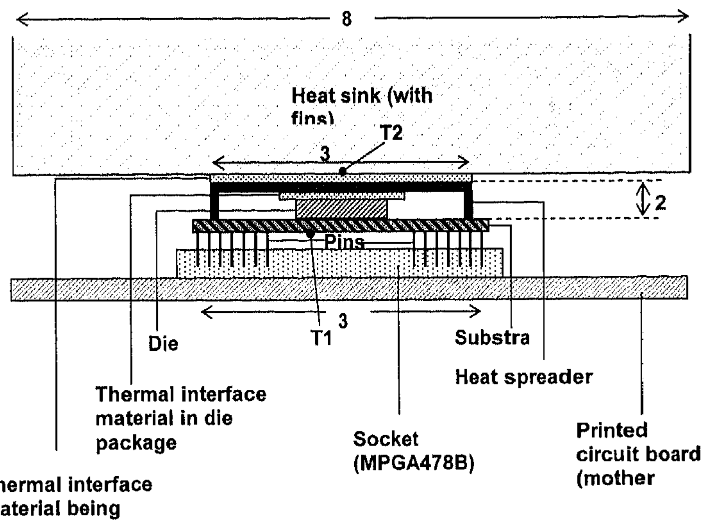


*Fig. 1 Experimental set-up using a computer for application-oriented testing of various thermal interface materials [28]. T1 and T2 are thermocouples. All dimensions are in mm.*

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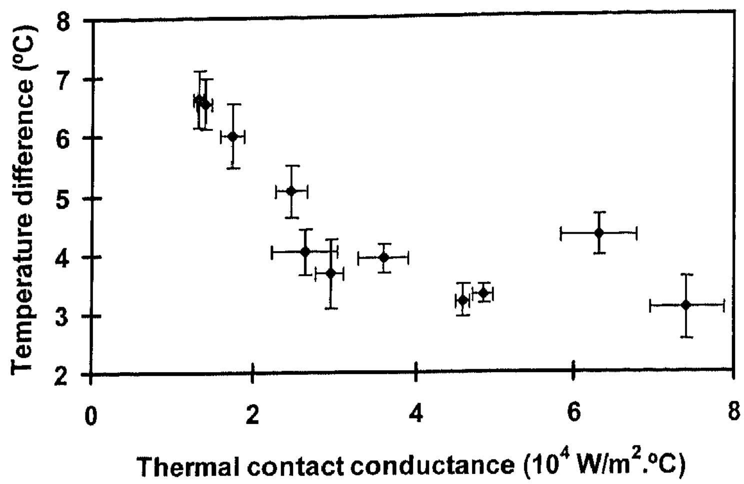


*Fig. 2 Temperature difference in computer testing vs. thermal contact conductance in Guarded Hot Plate measurement [28].*

aluminum foil that had been coated with each of the pastes on both sides were also included in the comparative study.

Table 1 shows the temperature difference obtained by application-oriented evaluation using the computer [28]. The best materials are carbon black by itself, Shin-Etsu by itself and Al coated with Shin-Etsu; the second best materials are flexible graphite coated with carbon black or Shin-Etsu and Al coated with carbon black; the third best materials are Arctic Silver by itself and aluminum coated with Arctic Silver. The superiority of carbon black and Shin-Etsu over Arctic Silver (each by itself) reflects the alignment and smoothness of the mating surfaces and the consequent thin gap at the interface. The thin gap favors an interface material that exhibits high conformability.

Table 1 also shows the thermal contact conductance obtained using the Guarded Hot Plate Method [28]. A low value of the temperature difference (based on application-oriented testing using the computer) correlates with a high value of the contact conductance in most cases. The main discrepancy pertains to the results for carbon black by itself and for Arctic Silver by itself. The temperature difference is lower for carbon black by itself than for Arctic Silver by itself, but the contact conductance is lower for carbon black by itself than for Arctic Silver by itself. This discrepancy is attributed to the greater smoothness of the microprocessor package than the copper surfaces used in the contact conductance measurement. The carbon black paste is more fluidic than Arctic Silver, so it has greater conformability, thus performing particularly well for smoother surfaces [10]. The heat sink surface is rough, so conformability to the surface topography of the heat sink can be attained for both carbon black paste and Arctic Silver. However, conformability to the microprocessor surface is attained to a greater degree by the carbon black paste than Arctic Silver.

Fig. 2 shows the extent of correlation between the results of application-oriented computer testing and those of thermal contact conductance measurement. A higher conductance correlates with a lower value of the temperature difference when the conductance is below 3 x $10^4$ W/m$^2$.°C (i.e., the temperature difference is above 4°C). When the conductance is higher, the temperature difference is essentially independent of the conductance. For example, thermal contact conductance measurement shows that Shin-Etsu by itself is more effective than carbon black by itself, but the values of the temperature difference obtained by computer testing are close for these two cases (Table 1). This behavior is due to the fact that the thermocouples used in the computer testing are separated by not only the thermal interface material, but also the microprocessor package, the substrate and the socket (Fig. 1). The separation makes the measured temperature difference substantial, even though the actual temperature difference across the mating surfaces may be small. Thus, the computer testing method is not suitable for evaluating high-performance thermal interface materials. A true assessment of the effectiveness of a thermal interface material is the measurement of the thermal contact conductance.

In conclusion, comparative evaluation of the relative effectiveness of various thermal interface materials shows that carbon black paste, whether by itself or as a coating on aluminum or flexible graphite, is

**Table 1 Temperature difference at 5 min of Pentium IV computer operation and thermal contact conductance for various thermal interface materials [28].**
FG = flexible graphite, Al = aluminum.

| Thermal interface material | Temperature difference (°C) | Thermal contact conductance ($10^4$ W/m$^2$.°C)* |
|---|---|---|
| Carbon black | 3.32 ± 0.16 | 4.85 ± 0.13 |
| Arctic Silver | 4.30 ± 0.39 | 6.31 ± 0.39 |
| Shin-Etsu | 3.07 ± 0.53 | 7.41 ± 0.47 |
| FG | 6.55 ± 0.43 | 1.40 ± 0.09 |
| FG + carbon black | 3.67 ± 0.27 | 2.93 ± 0.09 |
| FG + Arctic Silver | 6.01 ± 0.55 | 1.74 ± 0.15 |
| FG + Shin-Etsu | 4.04 ± 0.58 | 2.63 ± 0.18 |
| Al | 6.63 ± 0.48 | 1.32 ± 0.06 |
| Al + carbon black | 3.92 ± 0.24 | 3.67 ± 0.31 |
| Al + Arctic Silver | 5.06 ± 0.44 | 2.46 ± 0.18 |
| Al + Shin-Etsu | 3.27 ± 0.35 | 4.59 ± 0.48 |

* *Measured using the Guarded Hot Plate Method, with the thermal interface material between copper surfaces squeezed together at a pressure of 0.46 MPa (50 psi).*

more effective than silver paste (Arctic Silver), but is comparable in effectiveness to aluminum paste (Shin-Etsu). The carbon black paste by itself is as effective as the Shin-Etsu paste coated aluminum. The high effectiveness of the carbon black paste is due to its conformability. The Shin-Etsu paste is more effective than Arctic Silver, whether by itself or as a coating. The relative performance is mostly consistent with that assessed by measuring the thermal contact conductance. The correlation is good for conductance below 3 x $10^4$ W/m$^2$.°C. The discrepancy is attributed to the difference in surface roughness between computer and Guarded Hot Plate surfaces.

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