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Die Attach Epoxy Characterization for Electronic Assemblies

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ABSTRACT
Multi-chip modules frequently use epoxy-based die attach materials to adhere integrated circuits (ICs) to substrates. Comparisons based on technical data sheets alone are limited, especially when comparing across suppliers. Finite element modelling, frequently used for predictive analysis of stress and thermal performance, requires accurate temperature-dependent properties data. The aim of this work is characterization and performance-testing of die attach epoxies for current and future electronic assemblies. The information gathered using industry-standard or Sandia-developed material characterization tests were done with many epoxies and is more in-depth than technical data sheets. The documented test methods allow for reproducible data that enable comparisons of epoxies across a variety of suppliers. We compare the interim characterization data across a wide variety of die attach epoxies. The relationship between the cure process and the properties of the epoxies will be discussed.

Key words: die attach, epoxies, microelectronics adhesives

INTRODUCTION
Semiconductor chips are often attached to substrates, lead-frames, ceramics or printed wiring boards with die attach adhesives. This report covers characterization of some commercially available die attach adhesives that are used for wire bonded semiconductor die. This report does not cover flip chip products. The focus is on liquid or paste materials (A stage) versus partially cured films (B stage) die attach materials.

Die attach adhesives are typically polymer-based composites with non-polymer fillers. They are designed to adhere the silicon die to either organic or metal surfaces, such as solder mask, copper, gold, silicon, ceramics, or silver. The materials must accommodate thermal expansion mismatches between silicon and the substrate. Die attach also can provide a thermal path and/or electrical conductivity per device needs. The die attach does all of these without harming or contaminating the circuit. [1]

PROPERTIES CHARACTERIZATION
System and die attach requirements
System requirements for reliability, electrical performance, and manufacturability drive die attach derived requirements for multichip modules. Figure 1 illustrates the relationship between the die attach derived requirements with the system requirements. Reliability of die attach adhesives was probed by examination of their mechanical properties, strength and adhesion to interfaces, contamination, voiding, moisture diffusivity and cure parameters. Electrical performance is evaluated by measurement and determination of electrical resistivity, filler, thermal conductivity and diffusivity, heat capacity, adhesion strength, and voiding. Manufacturability is assessed by evaluating dispensability and consistency, cure conditions, voiding, resin bleed, and thermal stability.

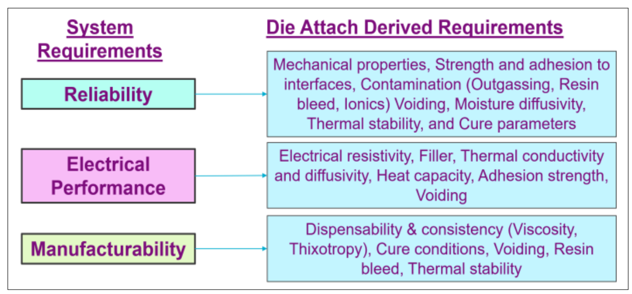

Figure 1. System requirements and derived requirements for die attach material

Characterization
Figure 2 provides a road map for characterization techniques to assess die attach materials reliability and electrical performance. The arrows in the map define when the order of the techniques is necessary in order to inform the next test being performed and property being examined.

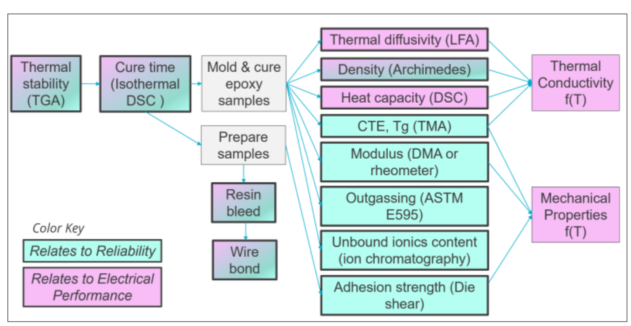

Figure 2. Die attach materials characterization

Thermal Stability
Thermal Gravimetric Analysis (TGA) was used to probe the thermal stability of eight different die attach materials. This TGA data is presented in Figure 3. Between 100 and 200C,

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the diluents and solvents evaporated from several die attach materials, which can cause voids and contamination in resultant electronic assemblies. Between approximately 350°C and 500°C, the polymers break down. The remaining mass after the TGA temperature sweep is the weight percent of the die attach adhesive filler.

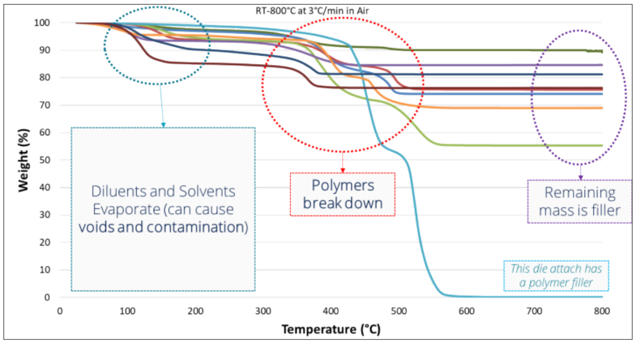

Figure 3. Thermal gravimetric analysis (TGA)

Die Attach Cure

Isothermal differential scanning calorimetry (DSC) was performed for each of the die attach materials. In this technique the die attach sample is placed in an uncured state into a DSC sample pan and heated from ambient conditions to the cure temperature of interest as rapidly as possible. In the cases illustrated in Figure 4 and Epoxy 1 in Figure 5, these samples are taken from ambient conditions to 175°C in less than two minutes. At this point the amount of heat put into the reference material is compared to the sample of die attach and that difference is measured. In the case of an epoxy die attach that heat flow is positive indicating that the epoxy is curing and releasing heat.

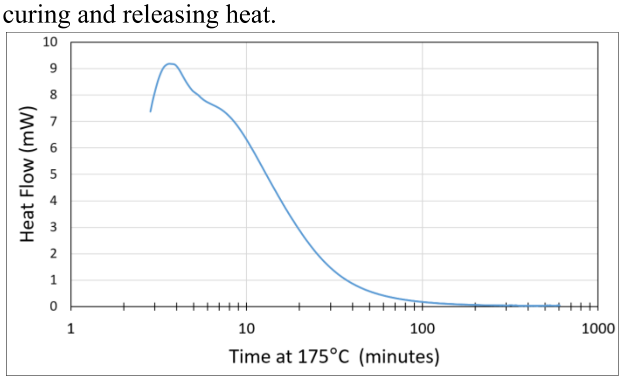

Figure 4. Differential scanning calorimetry (DSC) held isothermally at 175°C

The die attach is only fully cured when the heat flow has reached zero. The purple vertical lines in the figures represent what the die attach manufacture is suggesting for a cure. In all cases in this study the manufacturer's suggested cure is significantly less than a full cure of the material. For commercial applications this is typically adequate and will provide a part of acceptable quality. For military / aerospace / automotive /high reliability the under-cured condition will provide suboptimal material properties which often will impact the environmental robustness of the finished device.

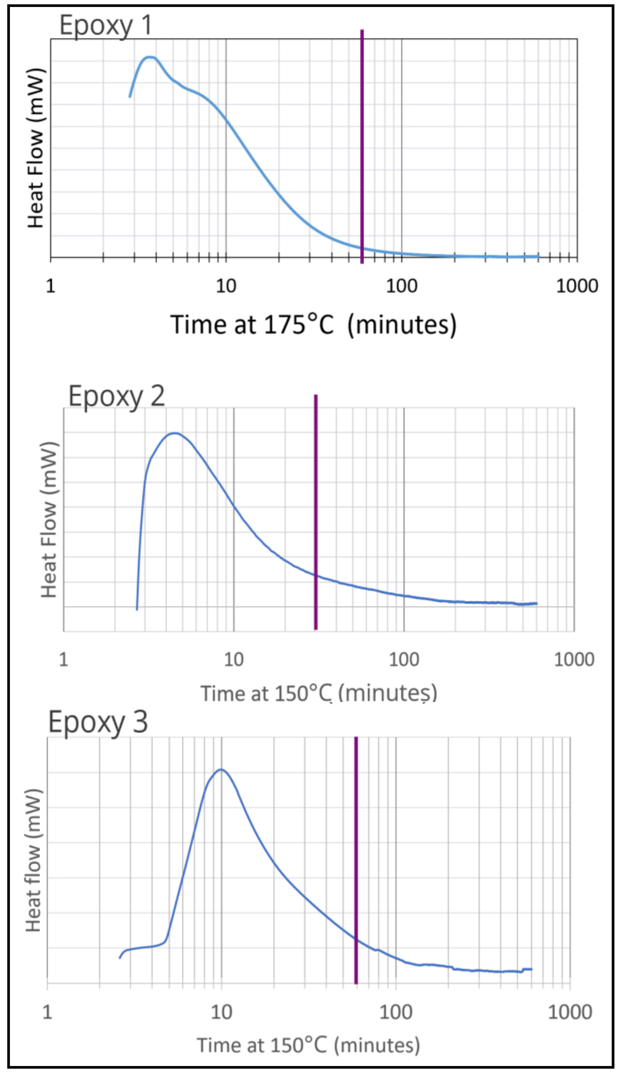

Figure 5. Differential scanning calorimetry (DSC) with a 10-hour isothermal hold vs heat flow. Purple lines are data sheet recommended cure time at the indicated temperature.

The impacted properties include but are not limited to mechanical properties such as coefficient of thermal expansion, glass transition temperatures, and modulus.

The cure temperature can also have dramatic effects on shear strength (Figure 6). The shear strength of the die attach epoxy increases dramatically with a higher cure temperature and a more complete cure.

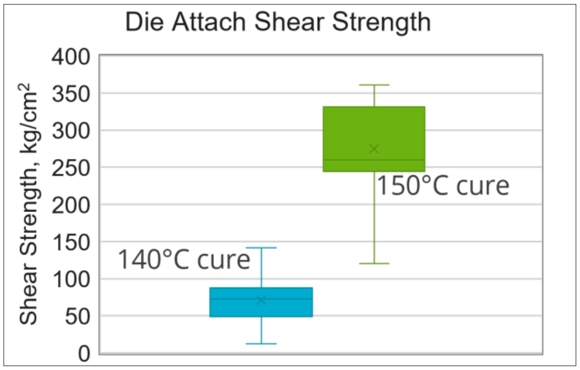

Figure 6. Die shear strength of the die attach epoxy increased over three times when cured at a higher temperature.

Table 1 shows the outgassing performance of an epoxy cured at three different temperatures. Vacuum outgassing performance is critical for space applications. ASTM E-595 specifies outgassing methods, which measure the total mass loss, total condensable matter, and water vapor of a cured material at 125°C in vacuum. [2] Maximum total acceptable mass loss is 1.00%. The outgas testing results for total mass loss improves with increasing cure temperature. Condensable matter did not significantly change with increasing cure temperature for this material.

Table 1. Outgassing performance versus cure temperature

Cure Temperature	Total Mass Loss
60°C	1.18%
71°C	0.91%
80°C	0.8%

Thermal Conductivity

Thermal conductivity is a critical property for devices that need significant removal of heat. Heat is generated in the active circuitry of the die, and if the heat is not transferred or dissipated, the junction temperature of the circuit will rise. High junction temperatures can harm the performance of the circuitry. In this work, thermal conductivity is not directly measured. It is calculated from thermal diffusivity, specific heat capacity and density. ASTM E1461-13 specifies the standard method for thermal diffusivity using the flash method. [3]

Thermal conductivity (λ) is a product of thermal diffusivity (α), specific heat capacity (Cp), and density (ρ). (Equation 1)

$$\lambda = \alpha \, Cp \, \rho \qquad \text{[eq 1]}$$

An instantaneous pulse of energy is applied to the front surface of a sample of a known thickness. The energy pulse transfers a known amount of energy to the front surface of the sample. On the rear face of the sample, the rise in initial temperature is measured versus time. The diffusivity value can be extracted from temperature vs time curve.

Thermal diffusivity measurements are graphed in Figure 6 for two different die attach epoxies at initial temperatures from -5°C to 125°C. The ASTM E1361-13 standard was followed, using Netzsch LFA 467 Hyperflash laser flash analysis (LFA) equipment. Two thicknesses of samples were used, with three runs per thickness. The graph is an average of the six total data points.

Two different types of commercially available die attach were measured. The data plotted at the top of the graph (orange line and data points) has a thermal diffusivity of ~3 mm^2/second. The type of die attach with the thermal diffusivity of ~3 mm^2/sec is a thermally conductive die attach epoxy highly filled with silver flake. The data plotted at the bottom of the graph (blue line and data points) has a thermal diffusivity of ~ 0.4 mm^2/sec. The type of die attach for the blue line is a non-conductive die attach with an inorganic non-metallic filler.

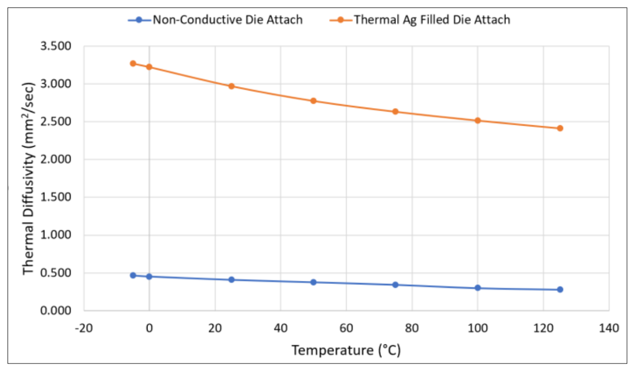

Figure 7. Thermal diffusivity measurements are graphed for two different die attach epoxies at initial temperatures from -5°C to 125°C.

The density of the die attach epoxies was measured by Archimedes method using distilled water, calibrated with a known density standard immediately prior to the test. A balance with 0.0001 mg accuracy was used. The average from three samples at room temperature were measured. Densities for temperatures above and below room temperature were calculated using thermal mechanical analysis (TMA) of cured epoxy. Method and equipment of the TMA is in the mechanical properties section of this paper.

Specific heat capacity was measured with differential scanning calorimetry (DSC) using ASTM E1269-11, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry. [3] Equipment used was a TA Instruments Q2000 series, performed with nitrogen sealed hermetic pans. Figure 8 shows the specific heat capacity as a function of temperature.

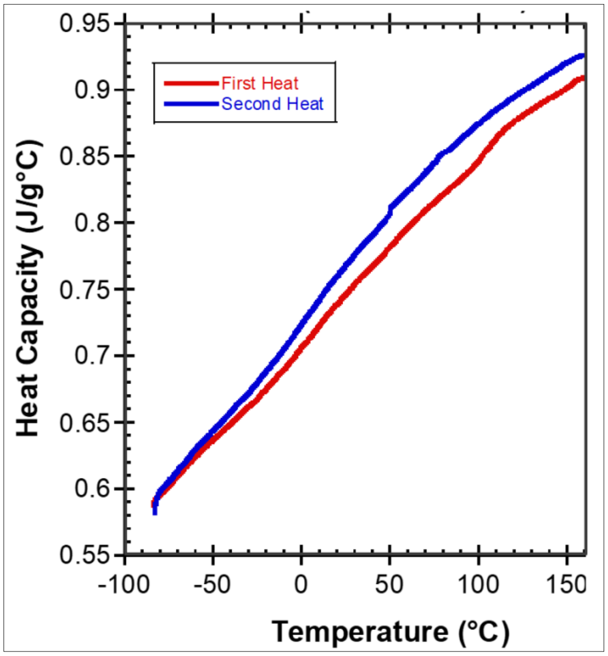

Figure 8. Specific heat capacity measurements are graphed at temperatures from -80°C to 150°C.

Thermal conductivity is graphed in Figure 8 for two different die attach epoxies at initial temperatures from -5°C to 125°C. Thermal conductivity was calculated using equation 1 and the experimentally measured values of specific heat capacity, thermal diffusivity, and density. The thermal die attach epoxy with silver filler has a thermal conductivity more than six times that of the non-conductive die attach.

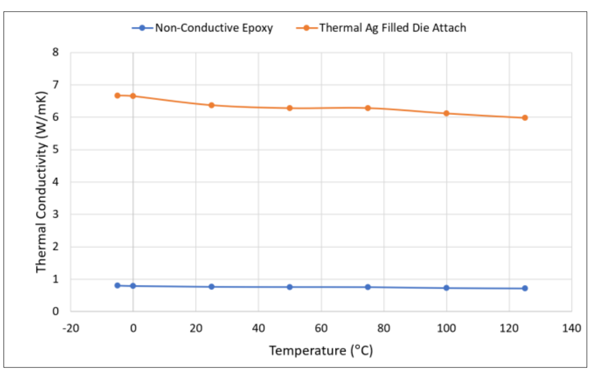

Figure 8. Thermal conductivity from -5°C to 125°C.

Coefficient of Thermal Expansion

Thermal mechanical analysis (TMA) is used to measure the elastic strain vs temperature. The cured epoxy die attach expands during heating and contracts during cooling. The thermal expansion coefficient is calculated by the slope of the strain curve. Figure 9 shows a graph of the experimentally measured strain vs temperature for two different cured die attach epoxy materials. Note that there is an inflection in the slope of the lines. Best-fit lines above and below the inflection points, represented by the dashed lines. The intersection of the dashed lines is the glass transition temperature.

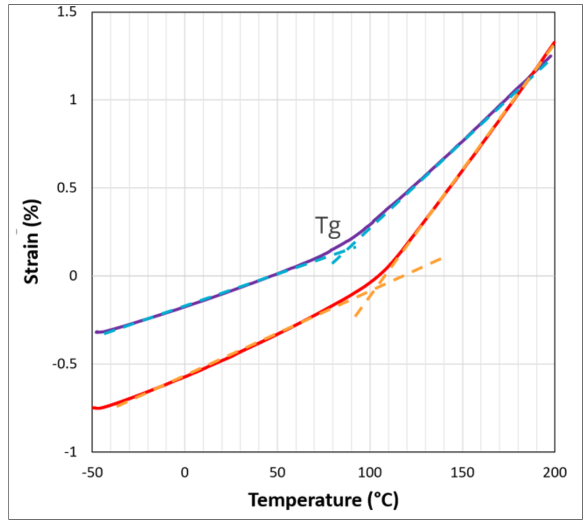

Figure 9. Linear strain for two materials is graphed at temperatures from -50°C to 200°C.

Modulus

Figure 10 shows the large variations among die attach epoxies in terms of storage modulus. The data is collected by an ARES G2 torsional rheometer. The cured sample is a long prismatic rectangle, clamped at both ends, and twisted in a 0.05% oscillation. This technique measures shear (storage) modulus rather than the tensile (Young's) modulus. High modulus materials are stiff, and low modulus materials are more flexible.

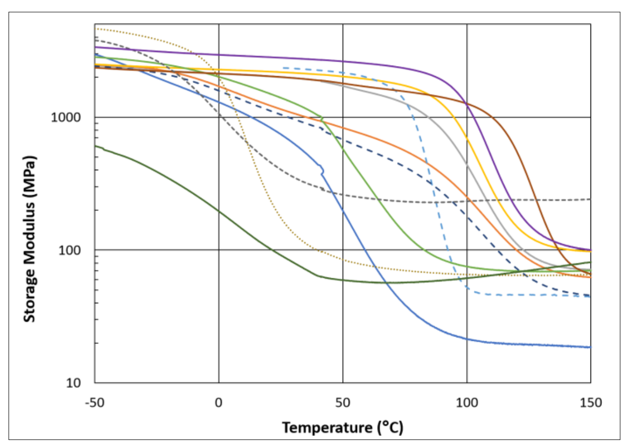

Figure 10. Storage modulus for 12 materials is graphed at temperatures from -50°C to 150°C.

Conclusions

Die attach material selections depend on the requirements of the system for which they are used. Material selections are critical because materials can affect reliability, manufacturability, and device functionality. Numerical modelling is used extensively in the design and prototyping process and can be instrumental in determining if a certain design or materials set is likely to meet system requirements. However, numerical models are only as good as the properties data that they use. Characterization of critical properties improves predictive modelling fidelity versus data sheet values.

To enable informed epoxy selection, start with the system requirements. Derive material requirements from system requirements and use properties data that are trusted. Finally, understand that cure profile affects the die attach properties, and that data sheets often understate cure times.

References

[1] J. a. S. D. Licari, Adhesives Technology for Electronics Applications Materials, Processing, Reliability, Elsevier, 2011.

[2] ASTM International Designation: E595-15 (Reapproved 2021), *Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment.*

[3] ASTM International Designation: E1461 - 13 (Reapproved 2022), *Standard Test Method for Thermal Diffusivity by the Flash Method.*

[4] ASTM International Designation: E1269 - 11 (Reapproved 2018), *Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry.*

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