A Thermally Enhanced Film Adhesive for Assembling High Power Density Electronic Devices

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Abstract

Assembly adhesives play a crucial role in packaging and thermal management design for microelectronics devices. The main function of the adhesives is attaching multiple components together to deliver designed functionalities and ensure integrity and reliability of the device. As requirements for performance and functionality increase, heat generated from these devices increases exponentially. For example, local heat flux can easily exceed 50 W/cm^2 for IGBT power modules while it may reach several hundred W/cm^2 at active areas for Gallium Nitride (GaN) power amplifiers. However, intrinsic thermal conductivity of polymer-based adhesives is around 0.2 W/mK, which increasingly becomes a thermal bottleneck in high power density electronics devices, especially those used in defense and aerospace systems. Effectively and safely dissipating the high heat and ensuring device reliability have become one of the critical tasks in the development of modern aerospace and defense systems.

This paper presents an adhesive film that uses non-electrically conductive particles with high thermal conductivity as fillers in the adhesive to enhance thermal transport. The adhesive film offers an effective thermal conductivity around 0.7 W/mK, which is more than a 3X improvement over conventional assembly adhesives. In addition, the film adhesive has a long work life at ambient conditions with significantly improved processability and controllability, such as bondline thickness control and uniformity, no voids/air pockets, no or minimum resin bleed, etc. They can also be easily converted into preforms with complicated shapes/geometries with typical tolerances less than 10 mil to facilitate assembly processes and ensure a clean and waste free environment.

Key words
RF power devices, thermal management, electronics packaging, adhesives, power modules, and RF grounding.

I. Introduction

Assembly adhesives play a crucial role in packaging and thermal management design for a microelectronics device. The main function of the adhesive is attaching multiple components together to deliver designed functionality and ensure integrity and reliability of the device. Commonly used adhesives are typically curable or thermoset materials, consisting of a polymeric resin, a hardener and fillers. The curing (or thermosetting) process is a non-reversible process, unlike solder reflow, which enables lower process temperature but higher operation temperatures. This process-friendly feature not only drastically extends the application of the assembly adhesives to areas beyond traditional solder territory, but also significantly improves creep resistance at the bonding area and thus enhances device reliability.

The polymeric resins typically include epoxy, acrylic, and silicone, etc. Epoxy offers excellent mechanical bonding performance and high thermal/chemical stability, which make it a workhorse in the adhesive family. The main weaknesses of epoxies typically include higher curing temperatures and longer curing times. Acrylics offers an alternative solution to offset these weaknesses. Acrylics allows faster curing (snap curing) at lower (or ambient) temperatures for high throughput applications. But its high temperature stability is poor. Silicones offer excellent high temperature stability as well as improved ability in handling CTE mismatched assemblies. But its bonding strength is typically orders of magnitude lower than epoxy or acrylic. Epoxy hardener systems include anhydride, imidazole, amine, peroxide, and others.

Intrinsic thermal conductivity of polymer materials is around 0.2 W/mK, which is effectively a thermal insulator and cannot be used in applications that involve high heat fluxes. To overcome this weakness, non-electrically conductive particles with high thermal conductivity (Table 1) are added as fillers in the adhesives. The traditional approach of adding fillers is to dispense/suspense a certain amount of the fillers in the polymeric resin matrix, which forms point-to-point contact between adjacent filler particles to conduct heat from one surface to the other.

Table 1: Commonly used non-conductive fillers.

Material	Thermal conductivity (W/mK)
Polymers	0.2
Silica	~1
Aluminum oxide	25-30
Magnesium oxide	30-40
Silicon carbide	100-200
Aluminum nitride	175
Boron nitride	100~700

Based on ambient state and application processes, assembly adhesives can also be classified as liquid adhesives and film adhesives, with liquid adhesives being the most common. Typically, liquid adhesives are applied using a dispensing tool or automated equipment. Conventional methods for applying liquid adhesives include needle dispensing, screen or stencil printing, pin or stamp transfer, and jetting. However liquid adhesives present a very limited work life upon application, which can range anywhere from minutes to hours. Significant effort is required to design a robust dispensing process (software/hardware settings), integrating variance in liquid viscosity, air entrapment effects and other dynamic variables affecting dispensing uniformity over complex patterns. These processing challenges are exacerbated when assembling components with large areas or complex geometries.

Film adhesives were developed to overcome the limitations of liquid adhesives. These adhesives are typically a blend of solid resins, hardeners, and fillers, produced in a dry sheet format [1]. One of the main differences that distinguish films from liquid adhesives is room temperature viscosity. A film's viscosity is typically several orders of magnitude higher than a liquid adhesive, which makes it more stable than liquids at ambient conditions. Consequently, film adhesives can be considered as a dry "B-staged" state which can be easily handled with a significantly longer work life – as long as six months in ambient conditions -- as compared to liquid adhesives. Additionally, film adhesives can be converted into different shapes and geometries to simplify their application process (Fig. 1).

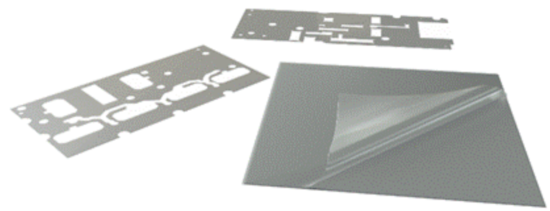


Fig. 1: Pictures of assembly film adhesive and preforms.

Benefits of film adhesives include:

- Even distribution of the adhesive over a large area and precise control of adhesive volume and location.
- Better control of a desired bondline thickness.
- Elimination of solvent evaporation during assembly and curing processes, which guarantees uniform and void-free bondlines.
- Better edge and flow control.
- Long work life.

These advantages make film adhesives more suitable for high-end applications involving large area assemblies, adherends with mismatched CTEs, tight and accurate bondline control requirement and a waste-free and clean processes. Typical applications include communication systems, wireless base stations, power amplifiers, radar and sonar systems and hybrid packaging.

However, with the broad adoption of cutting-edge semiconductor technologies in automotive, telecom, aerospace and defense systems, higher power conversion levels combined with increased functional demand, now require assembly adhesives and processes to cope with more challenging thermal, electrical and mechanical performance, paired with long-term reliability requirements. Consequently, the demand for high thermally conductive adhesive solutions delivering reliable mechanical bonding, high thermal conductivity and robust electrical performance is immense [2].

This paper presents a high thermally conductive film adhesive for high power density electronics packaging. The material meets Mil 883 method 5011 requirements [3]. The film adhesive is based on an epoxy resin matrix and processed by drying a liquid suspension coated onto a surface. Ceramic fillers are added to the film to enhance heat transfer. Two release liners are attached on the top and bottom surfaces of the film to protect it from dust, moisture, and/or other contaminants. Its basic structure is shown in Fig. 2. The release liners are typically paper or polyester (Mylar).

Fig. 2: Basic structure of the new film adhesive

II. Experimental Study

Comprehensive tests were conducted to characterize post-curing material properties as well as determine key performances of the film adhesive.

A. Curing Characteristics

Differential scanning calorimetry (DSC) was performed with a sample of approximately 14 mg to determine the curing schedules of the film adhesive. The DSC is a thermo-analytical technique in which the amount of heat required to increase the temperature of a sample relative to a reference material is measured as a function of temperature. Both the sample and reference were maintained at the same temperature throughout the experiment. The DSC curve (Fig. 3) of the new adhesive indicated that an intense chemical reaction (or curing mechanism) initiated around 117º C and peaked at 150ºC.

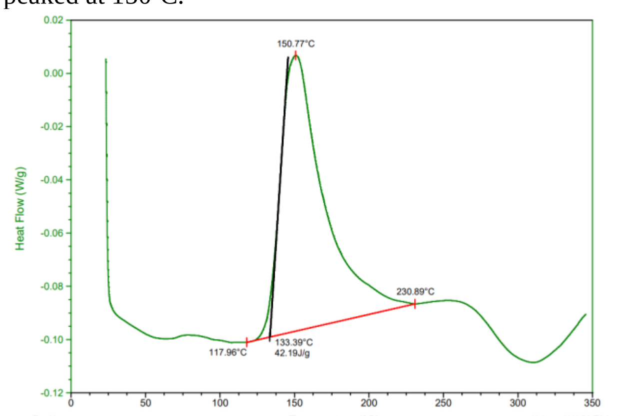


Fig. 3: DSC curve of the new film adhesive

The isothermal DSC method was used to study the crystallization kinetics of the new adhesive. The ramp rate was 5º C/min. The curing temperature was set at 150º C. The test (Fig. 4) indicated that it took 55 minutes to fully cure the adhesive sample. The recommended curing time at 150º C is 60 minutes to ensure the fully cured state.

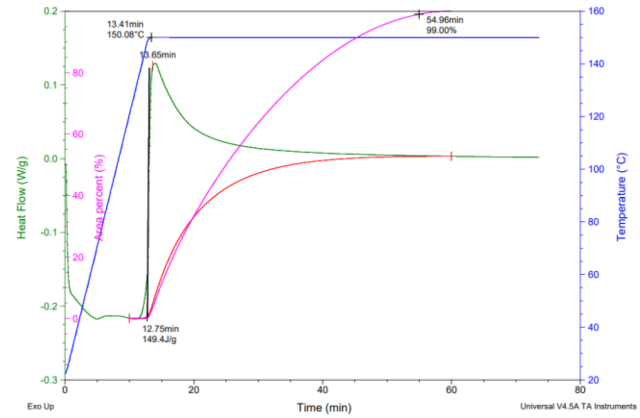


Fig. 4: Isothermal DSC of the new film adhesive

B. Outgassing Test

Outgassing is a serious concern for all electronic equipment intended for use in aerospace and many defense systems which operate in high-vacuum environments. Therefore, the volatile components content of the adhesive was evaluated according to the ASTM E595-15 standard [4]. These tests were performed in a vacuum environment of less than 5x10-5 torr for a duration of 24h at 125º C. The total mass loss (TML) collected volatile condensable materials (CVCM), and amount of water vapor recovered (WVR) are reported in Table 3. Historically, a TML of 1% and CVCM of 0.1% have been used by NASA as screening standards for spacecraft materials. The outgassing tests indicate that the film adhesive meets these stringent NASA outgassing standards.

Table 3: Outgassing test results

	New film adhesive	NASA criteria	Comments
Total mass loss (TML)	0.4%	<1%	Pass
Collected volatile condensable materials (CVCM)	0.0	<0.1%	Pass
Water vapor recovered (WVR)	0.24%	Monitor only	-

C. ThermoMechanical Analysis (TMA)

As mentioned above, CTE is another critical property of a cured adhesive. TMA test was conducted to determine CTEs of a fully cured adhesive test specimen. The specimen had a size of 2.8 mm. As shown in Fig. 5, the size of the sample increased as its temperature increased. The dimensional change from subzero to 105 ºC was almost linear with a slope approximately 0.1 µm/ºC, which indicates that the CTE of the adhesive is around 36 ppm/ºC for temperatures below 80 ºC. As the temperature was further increased, the dimensional change accelerated with the slope jumping to 0.65 µm/ºC, which represents a drastic volumetric expansion of the material. This can be explained by the fact that the epoxy-based adhesive is a polymer material. Unlike metals, polymer materials (i.e., epoxy, acrylic, silicone, etc.) typically demonstrate a hard and brittle "glassy" state at low temperatures while they become more flexible and rubberier at elevated temperatures. The temperature range between the two states is referred as glass transition temperature. CTE at the glassy state is typically much lower than that at the rubbery state.

The TMA test indicates that the new film product has a glass transition around 113 ºC. When operational temperature exceeds 113 ºC, the CTE of the adhesive increases by more than 6 times, which may cause stress concentration and thus delamination risks. A thorough reliability studies need to be conducted if the film adhesive is used in applications with operational temperatures that are high, especially over 113 ºC.

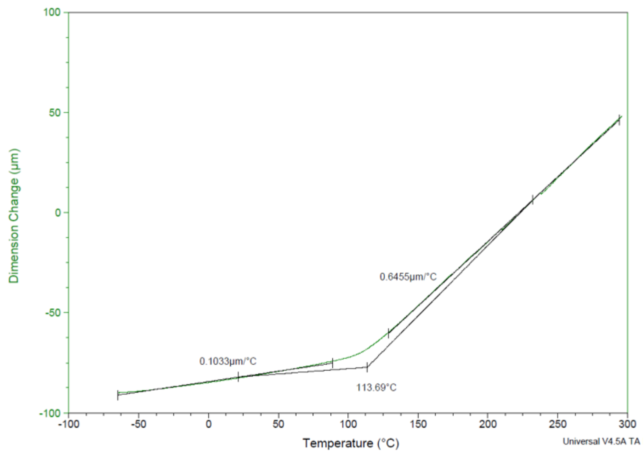


Fig. 5: TMA test results

D. Dynamic Mechanical Analysis (DMA)

Modulus plays a key role in the bonding performance of an adhesive. Adhesives with a higher modulus typically form a more rigid bond with higher bonding strength. However, a rigid bond can lead to stress concentration when bonded parts are exposed to thermal cycling conditions, especially for those with larger bonding areas and significantly mismatched coefficients of thermal expansion (CTE). Conversely, adhesives with a lower modulus typically create a flexible bond, which is insensitive to the CTE mismatch induced stress concentration. However, adhesives with very low modulus might have problems to maintain enough bonding strength required by typical applications. Practice indicates that an adhesive with a modulus above 1 GPa can meet bonding strength requirements in typical microelectronics assembly applications.

DMA is a widely used technique to study and characterize the modulus of a cured adhesive. It is most useful for studying the viscoelastic behavior of polymers. The DMA study indicated that the modulus of the film adhesive decreased significantly at around 100 ºC, which typically suggests a reduction of bonding strength. However, the modulus still remained above 1.5 GPa to temperatures up to 200 ºC (Fig. 6), which may indicate acceptable and stable bonding strengths in high operation temperature conditions. To verify the hypothesis, bonding strength tests are needed.

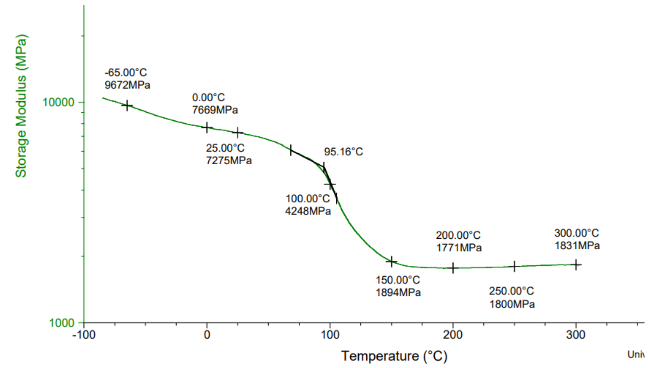
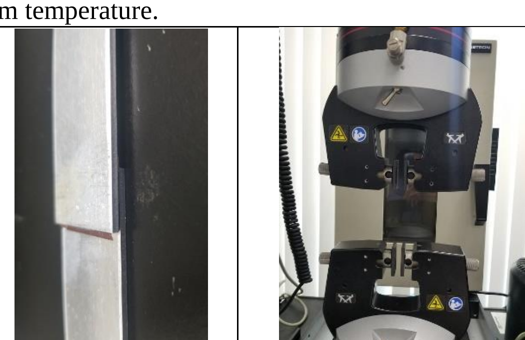


Fig 6: DMA test results

E. Bond Performance

Lap shear strength is one of the best indicators of the bonding strength of adhesives. Lap shear panels made of Chromate etched aluminum panels (101.6mm X 25.4mm X 1.62mm) were assembled to measure the film's adhesion strength. Samples of film adhesives measuring 12.7 mm X 25.4 mm were cured between two aluminum (Al) panels to create a ½" long bonding area (Fig. 7a). Clamps were applied during the curing process to provide a constant pressure of approximately 10 Psi. The tensile lap shear tests were conducted with an Instron 5566C8995 system (Fig. 7b) at room temperature.



(a) Test Specimen | (b) Instron 5566C8995

Figure 7: Lap shear test specimen and equipment

To evaluate the bonding performance, lap shear tests were performed at three temperatures (25 ºC, 50 ºC, and 125 ºC). The test results (Fig. 8) indicated that the lap shear bonding strength decreased slightly when temperature increased from 25 ºC to 50 ºC. However, the strength dropped to 1000 Psi with a reduction of more than 50% when the evaluation temperature exceeded the Tg of 113 ºC. However, the bonding strength was still around 1000 Psi, which meets bonding the strength requirements of typical applications. The test results were consistent with findings of the DMA study.

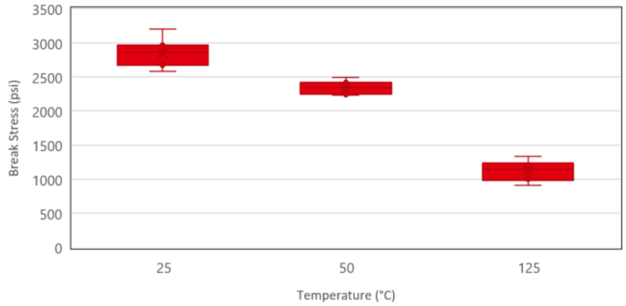


Fig. 8: Lap shear bonding strength

F. Thermal Performance

The lap shear tests demonstrate that the film adhesive offers excellent mechanical performance. However, high thermal performance is essential to ensure that the adhesive can be used in advanced packaging and high-end devices.

A Netzsch laser flash LFA 467 equipment was used to evaluate thermal performance of the film adhesive. The test method was based on three-layer laser flash principles. Gold-plated copper disks with a diameter of 12.7 mm and a thickness of 0.5 mm were fabricated for building the test specimen. The film adhesive was used to bond a pair of the disks together (Fig. 9).

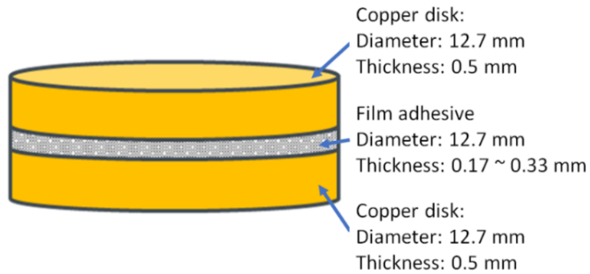


Fig. 9: Tri-layer test specimen for laser flash tests

The three-layer laser flash tests can provide a comprehensive assessment of the overall thermal performance, which factors in both the interfacial contact resistance and the intrinsic thermal resistance of the adhesive. This performance orientated parameter is also conveniently referred to as "effective thermal conductivity", to distinguish it from the intrinsic thermal conductivity of a material. Table 4 illustrates the effective thermal conductivity of the cured adhesive as a function of the final bondline thickness. For comparison, the effective thermal conductivity of conventional adhesive films is around 0.2 W/mK. It appears that the film adhesive presented an effective thermal conductivity of more than 3 times high than conventional adhesive films.

Table 4: Effective thermal conductivity

	Sample 1	Sample 2	Sample 3
Values (W/mK)	0.7	0.7	0.8

III. Conclusion

Comprehensive experimental tests have been conducted to evaluate curing characteristics, mechanical properties, and application performance of a high thermally conductive film adhesive. The test results indicate that this film adhesive presents a high bond strength while delivering a thermal performance which significantly exceeds that of commonly used adhesive films. In addition, the film adhesive also exhibits excellent stability in operation temperatures above its Tg, which may indicate high reliability for typical aerospace applications.

Acknowledgment

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