Investigation and Evaluation of High-Temperature Encapsulation Materials for Power Module Applications

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Abstract

With the advent of ultra-wide bandgap (UWBG) semiconductor materials, such as Gallium Oxide (Ga_2O_3) and Aluminum Nitride (AlN), higher temperature and higher voltage operation of power devices is becoming realizable. However, conventional polymeric and organic encapsulant materials are typically limited to operating temperatures of 200 °C and below. In this work, six materials were identified and evaluated as candidates for use as encapsulants for operation and high-voltage insulation at and above 250 °C. High-temperature silicone gel was used as a reference material and was compared to five novel encapsulants including an epoxy resin, a hydro-set cement, two low melting point glass compounds, and a ceramic potting compound. Gas pycnometry was utilized to evaluate the voiding concentration to avoid partial discharge. Each material was then processed onto a direct-bonded-aluminum (DBA) substrate test coupon to evaluate compatibility with a commonly used metal-ceramic substrate and processability for use in a power module. The insulation capability of each material was evaluated by testing the partial discharge inception voltage (PDIV) across a 1mm gap etched in the substrate. The dielectric stability was then tested by soaking the materials in air at 250 °C for various intervals and observing the degradation of their PDIVs and appearances. The results of each test were compared, and conclusions were drawn about each material's feasibility for use as a dielectric encapsulation material for a power module operating at temperatures exceeding 200 °C.

Key words

packaging, high-temperature, ultra-wide bandgap semiconductor, power module, encapsulation

I. Introduction

Encapsulation materials must play several critical roles to achieve successful operation and reliability of power electronics modules. They provide protections against electrical breakdown, chemical erosion, moisture absorption, hazardous radiation, as well as relief of mechanical stresses and shock [1]. Conventional power electronics packages, like that pictured in Fig. 1, have been designed and optimized for use with silicon semiconductor devices which are limited to approximately 150 °C operation due to the intrinsic carrier concentration of Si. With the low intrinsic carrier concentration and UWBG of new semiconductor materials, i.e. $1.79*10^{-23}$cm^{-3} and 4.8 eV for Ga_2O_3 respectively, the promise of high-temperature and high-power operation is realizable [2-4].

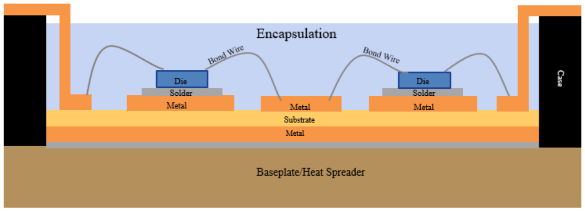


Figure 1: Common Power Module Architecture

Though these new devices theoretically have a much higher-temperature operating limit, conventional packages use polymeric encapsulation materials which are typically restricted to an operating temperature of 175 °C [5]. Acrylic, polyurethane, epoxy, and silicone encapsulation materials are limited by their glass transition temperature (T_g) and thermal decomposition [6], [7]. Increasing the operating temperature has several benefits including reduction of heavy and expensive cooling systems used to cool many of the commercially available power modules today, increased thermal reliability of existing systems, and the potential to operate in much higher ambient temperature environments [8]. The current power electronics package requires innovation to support the high-temperature operation permitted by the next generation of semiconductor devices. This work provides criteria for high-temperature encapsulation materials, performs a survey of potential candidates, and conducts a series of tests to evaluate their compatibility for use in a power module application as well as their high-temperature electrical durability.

II. Criteria and Selection

A. Requirements and Considerations

Keeping in mind the aforementioned roles of an encapsulation material for a power module, Table I below summarizes critical properties for the evaluation of potential materials.

Table I: Critical Encapsulation Properties

Property		**Desired Value**
Electrical	Dielectric strength	≥ 10 kV/mm (Or as needed for application)
	Dielectric constant	< 5
Thermal	Glass transition temperature (T_g)	> Working temperature (°C)
	Thermal conductivity (k)	> 1 (W/mK) (As high as possible)
	Processing temperature	< Safe component temperature
Mechanical	Coefficient of thermal expansion(α)	Matched to device, die attach and substrate (ppm/K)
	Elastic modulus (E)	4-10 (GPa)
	Viscosity (η)	< 20 Pa-sec for underfill (50 for encapsulation)

The dielectric requirements are established in the standard IEC 61287, which defines testing requirements for the PDIV and breakdown of passivation materials for converter applications [9]. These values will be dependent on the voltage level of the application, but it should be noted that the PDIV of materials has been shown to decrease by up to 53% over a temperature range of 25-250 °C [7], so appropriate scaling should be considered and testing performed in the design process.

Temperatures should be kept below the manufacturer prescribed glass transition and operating temperatures unless materials are subjected to high-temperature storage lifetime (HTSL) and thermal-cycling reliability tests within the desired configuration. Conventionally used encapsulants like epoxy molding compounds have low thermal conductivities. Packages targeting higher-power levels require low junction-to-ambient thermal resistance to maintain temperatures below component maximums and achieve manageable thermomechanical stresses inside the package [10]. Therefore, a material with higher thermal conductivity should be selected so long as they meet the other application requirements. There have been efforts to add silica and hexagonal boron nitride fillers to increase the thermal conductivity of conventionally used polymeric encapsulation materials; however, this leads to an increase in viscosity which may limit the composite material's use for double side cooled (DSC) and flip chip applications [11], [12]. In addition, the processing and curing temperatures for each material must be kept below a safe temperature for all components of the package (i.e. interconnect melting temperature, device annealing temperature).

Lastly, close attention must be payed to the mechanical concerns during processing and the thermo-mechanical stresses that arise when operating at elevated temperatures.

The encapsulant's coefficient of thermal expansion (CTE) should be matched as closely as possible to the other module components (i.e. devices, die attach, substrate) as CTE mismatch is the primary source of thermo-mechanical stresses in a package when operating at elevated temperatures [13]. It has also been demonstrated that having an elastic modulus between 4-10 GPa, which is higher than typical epoxies and gels and similar to that of many resin materials, can be beneficial in increasing the reliability of both conventional and DSC packaging configurations [14], [15]. Finally, the uncured viscosity must be sufficiently low so that the encapsulant can flow under the smallest facet of the package and be entirely outgassed. As such, a viscosity of 20 Pa-sec is desirable for DSC and flip chip configurations [16].

B. Potential Materials

Now that the criteria for a high-temperature encapsulation material has been established, a survey was conducted of potential options. This survey was conducted with the goal of compatibility with a 1.2 kV Ga_2O_3 power module targeting of 300°C operation. As such, the desired CTE has been tailored to match that of Ga_2O_3. Junction side cooling will be employed, so a sufficiently low uncured viscosity is required to be able to flow under a 0.5 mm facet. Results of the survey can be found in Table II below. Two additional materials, cyanate ester [17] and benzocyclobutene [18], were identified as potential candidates due to their high T_g; however, due to limited commercial availability, they were not included in the following survey or testing.

III. Test Procedure and Rationale

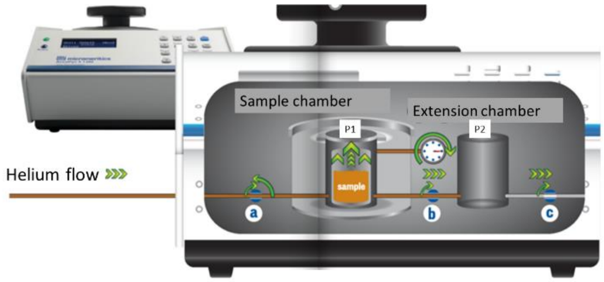
A. Gas Pycnometry

Unless processed in an inert environment, pockets of entrapped gas, commonly referred to as voids, can create areas of lower dielectric strength [19], [20]. As such, particular care must be taken in processing and fabrication of encapsulation materials for consistent and predictable performance. Gas pycnometry can be used to establish the density of a sample with known volume to estimate the concentration of entrapped gas per the USP 699 [21]. Fig. 2 depicts the test setup used and as the various fabricated samples can be seen in Table III below. Helium gas is used due to its small particle size and the difference in pressure between the reference chamber and the chamber containing the sample can be used to find the voiding

Table II: Requirements and Survey of Potential Materials

Property		Desired Value	Silicone Gel (NuSil 2188)	Epoxy Resin (Durapot 863)	Hydroset Cement (Ceramacast 675-N)	Ceramic Potting Compound (Durapot 801)	LMP Glass (Schott 339)	LMP Glass (Schott 393)
Electrical	Dielectric strength (kV/mm)	≥10	19.5	21.65	11.81	13.78	N/A (assumed high)	N/A (assumed high)
	Dielectric constant	<5	2.9	3.5	-	-	8.4	11.6
Thermal	Glass transition/operating temperature (ºC)	>300	250	314	1100	N/A	325	325
	Thermal conductivity (W/mK)	>1 (high as possible)	N/A (assumed low)	1.3	N/A (assumed high)	1.15	N/A	N/A
Mechanical	CTE (ppm/K)	3.77 (ideally) or < 20	N/A	3.4	5.6	4.3	4.7	4.7
	Elastic Modulus (GPa)	4-10	<1	2.65	N/A (assumed high)	N/A	58	58
	Viscosity (Pa-sec)	< 20	13	2	15	2.8	50+	50+
	Processing temperature (ºC)	<300	150	350	22	22	510-600	420-500

concentration. There are two limitations to this setup from a power module perspective. First, the sample size is limited to 1.85 cm x 3.95 cm which does not allow for flexibility in testing a complete configuration. Second, if there are any hermetic voids entrapped with openings smaller than that of a helium particle, they may not be included in the relative density calculation. If further voiding is evident or suspected SEM or x-ray imaging may be necessary to garner a more exact result.



$$V_{sample} = V_{sample\ chamber} - \frac{V_{expansion\ chamber}}{\frac{P_1}{P_2} - 1} \qquad D_{sample} = \frac{M_{sample}}{V_{sample}}$$

Figure 2: Gas Pycnometry Setup [22]

Table III below summarizes the results from the gas pycnometry testing both directly after the samples have been produced as well as after a 250 °C soak in air for 50 hours in order to correlate a potential increase in voiding concentration to a decrease in PDIV and breakdown strength of each material in the testing described in a subsequent section.

As anticipated, the porosity of the liquid binder ceramic-based materials was higher because outgassing was performed before and not during the cure, allowing gasses to be entrapped as the liquid evaporates during the curing process. An expected slight increase in porosity was seen uniformly across the board when the materials were thermally aged and burned in, with the only considerable degradation observed being the ceramic potting compound; exhibiting a 12% increase in average porosity.

B. Substrate Compatibility and Processability

The next test was to attempt to process each of the materials onto a DBA substrate to judge if the manufacturer supplied cure profile yields a proper encapsulation of the commonly used metal-ceramic substrate. This was a qualitative test to establish the feasibility of each material for use in a power module.

The silicone gel and epoxy resin were both easily outgassed and processed with no visible voids and sufficiently low viscosity to fill the 1mm gap between pads on the substrate (the rationale for the configuration will be discussed in the following section). The hydroset cement was also low enough viscosity to fill the small facet, and could be effectively outgassed with only small surface dimples forming after curing.

The low melting point glass composites required significantly higher processing temperatures, 420 °C and 510 °C for fusing temperatures from the frit and 500-600 °C for melting sufficient to pour. Even with pre-heating the substrates and a slow cooling time, large cracks formed through both glass samples similar to what was observed in Liu et al. [22]. In addition, when pouring, the molten glass was still quite viscous with no opportunity to outgas without a high-temperature vacuum furnace. While polyimide CTE buffers and other manufacturing techniques could be implemented to potentially successfully use these materials, they were eliminated from contention due to the difficult and high temperature processing.

Table III: Gas Pycnometry Test Results

	Silicone Gel (NuSil 2188)	**Epoxy Resin (Durapot 863)**	**Hydroset Cement (Ceramacast 675-N)**	**Ceramic Potting Compound (Durapot 801)**	**LMP Glass (Schott 339)**	**LMP Glass (Schott 393)**
						
Porosity Unaged	13.6%	13.3%	40.7%	34.5%	19.1%	32.1%
Porosity 50 Hour Soak at 250 ºC	15.3%	18.3%	45.4%	46.55%	19.3%	32.7%

Lastly, the ceramic potting compound was unable to be degassed due a very short potting life that caused it to harden in the vacuum chamber, forming large pockets of air inside the material. In addition, the material formed deep cracks during the cure profile losing its adhesion to the substrate and falling away. As such, the ceramic potting compound was also deemed inadequate for this use case and not investigated for its electrical properties.

C. Baseline PDIV and HTSL Reliability

Now that the materials have been down selected based on their compatibility and processability for power module applications, the electrical capability of the three remaining materials must be tested. In order to characterize the electrical insulation of each material, test coupons were fabricated as show in Fig. 3 below. Two bent silver leads were sintered to a DBA substrate. A 1 mm gap, a common spacing in power modules, is etched between the conductive pads of metal on the top side and the encapsulation is then processed on top. The bottom metallization is not removed as this is commonly used for connection to a baseplate.

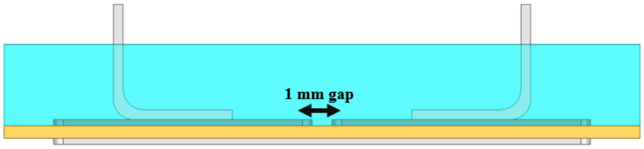


Figure 3: PDIV Test Coupon

Tests were performed by an Omicron MPD600 system following the method described in IEC60664 depicted in Fig. 4 below [23]. One of the Ag leads was connected to the HV electrode while the other lead and the bottom metal are grounded. The whole fixture is then submerged in electrical insulation oil in order to ensure that the PD and breakdown occurs between the conducting traces on the substrate.

A 60-Hz sinusoidal-signal is applied and is ramped from 0 V at approximately 100 V/s. This is monitored and recorded through the MPD software to track PD events as well as breakdown.

To test the high-temperature stability of each encapsulant, identical samples were fabricated and soaked at 250 ℃ in air. Subsets of three samples were tested at different intervals; unaged, 50 hours, and 100 hours. The results from these tests as well as photos of the samples can be seen in Table IV and Table V respectively.

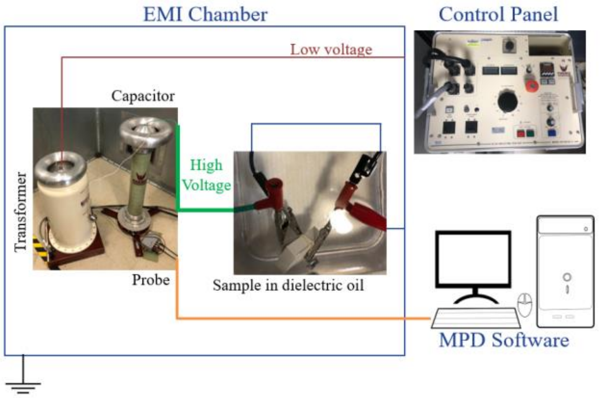


Figure 4: PDIV Test Setup

The PDIV of the silicone gel degraded by 35% as was in line with previous works on polymeric encapsulations [7]. Interestingly, the breakdown strength was largely unaffected, even increasing slightly after being aged which is theorized to be due to further vulcanization of the rubber, but further investigation is necessary to confirm this hypothesis [24].

Next, the epoxy resin saw an initial drop of 32% and 35% for the PDIV and breakdown strength respectively, but no further degradation was observed between the 50- and 100-hour aging steps, suggesting good sustained electrical performance event when exposed to elevated temperatures.

Lastly, the hydroset cement exhibited no PD events, instead reaching breakdown at ~2kV. While this was significantly lower than the other materials tested, no degradation was observed once again highlighting its potential as a high-temperature stable encapsulation material.

From a visual and mechanical standpoint, slight discoloration of the silicone can be seen with aging but no visible cracking or deformation occurred. The epoxy resin grew significantly darker in color and some cracks appeared along the surface. Lastly, the cement saw no real observable changes which was anticipated due to its high-temperature stability rating from the manufacturer.

Table IV: PDIV and Breakdown Test Results

	Silicone Gel (NuSil 2188)	Epoxy Resin (Durapot 863)	Hydroset Cement (Ceramacast 675-N)
Unaged PDIV	8.13 kV	6.37 kV	-
Aged 50 Hours at 250 ℃ PDIV	7.90 kV	4.31 kV	-
Aged 100 Hours at 250 ℃ PDIV	5.28 kV	4.76 kV	-
Unaged Breakdown	12.78 kV	11.18 kV	1.62 kV
Aged 50 Hours at 250 ℃ Breakdown	12.15 kV	7.25 kV	2.01 kV
Aged 100 Hours at 250 ℃ Breakdown	13.27 kV	7.92 kV	1.94 kV

Table V: PDIV Samples
Unaged vs. Aged 100 Hours at 250 ℃

Material	Unaged	100 Hours
Silicone Gel (NuSil 2188)		
Epoxy Resin (Durapot 863)		
Hydroset Cement (Ceramacast 675-N)		

IV. Conclusions

While initially selected as a reference material, the silicone gel performed adequately for use in a power module configuration with temperatures up to 250 ℃ exhibiting PDIV and breakdown strengths after aging of 5.28 kV and 13.27 kV respectively. Though some cracking did occur, the epoxy resin was also identified as a good candidate for these high-temperature applications showing effectively no degradation between the 50- and 100-hours aging interval. Finally, the hydroset cement seems to be limited to lower voltages than the other materials, assumedly due to its high porosity, exhibiting breakdown at ~2 kV, but is very thermally stable and has an assumedly higher thermal conductivity than the other materials tested.

As a continuation of this work, testing at higher-temperatures and/or for longer thermal soak times (out to 1000 hours) should help in the material selection process. In addition, performing the PDIV testing at elevated temperatures and over repeated partial discharge events should garner a clearer image of the electrical stability of these materials at high-temperature.

To better understand the mechanical resilience of the materials, thermal gravimetric analysis could be implemented to establish the decomposition point of each material to observe the upper limits of potential operating temperatures. Finally, testing the adhesion strength between the encapsulation material and the substrate through the use of shear tests with thermal aging intervals could be an effective way to establish a high-temperature mechanical reliability of the encapsulation/substrate interface.

To close, encapsulation materials were identified and tested for use in tandem with UWBG semiconductor materials for high-temperature power module applications which will assist in unlocking the full benefits that these next generation devices have over conventional Si based technologies.

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