

Evaluation of a Novel Dielectric Material for Aluminum Substrates

Michael Creamer, Mark Challingsworth, Samson Shahbazi

Heraeus Materials Technology LLC, Thick Film Materials Division

24 Union Hill Road, West Conshohocken, PA 19428

Ph: (610) 825-6050, Fax: (610) 825-7061, mike.creamer@heraeus.com

Abstract

Thermal management of high heat flux devices such as wide band gap devices, concentrated photovoltaics (CPV), and light-emitting diodes (LEDs) remains a major area of concern. Increases in power density mandate the need for packaging with low overall thermal resistance. This is especially true for light-emitting diodes (LEDs), an industry which many expect to eventually overtake incandescent and fluorescent lighting. Chip-on-board assembly provides minimal thermal resistance as long as a highly thermally conductive substrate is used. Aluminum is a very good heat sink material for this purpose due to its high thermal conductivity (up to 220 W/m-K) and low cost. In order to electrically isolate the substrate, a dielectric base layer must be placed on the aluminum. This material must exhibit good thermal conductivity and breakdown voltage, and must be a close match to the coefficient of thermal expansion (CTE) of aluminum ($\sim 25 \times 10^{-6}/^{\circ}\text{C}$).

This paper compares the performance of a lead-free thick film dielectric material on different aluminum alloys. The reliability of several dielectric properties will be examined, as well as the materials thermal conductivity and bowing deflection.

Key words: thick film, insulated metal substrate, heat sink, aluminum, lead-free

Introduction

Thermal management plays a vital role in many industries, especially light-emitting diodes (LEDs), where efficiency and light output are extremely dependent on the temperature of the die. The increasing power density of LED packages coupled with the growing popularity of LED technology creates the need for a cost-effective and thermal dissipative packaging system.

Aluminum exhibits many advantages as a heat-sink material for high volume applications, such as low cost and excellent thermal conductivity (160-220 W/m-K depending on purity/alloy). However, an electrically insulating layer is necessary between the aluminum and the top conductor to prevent shorting of the circuit, without inhibiting the overall thermal conductivity of the system. The total thermal resistance of this layer depends upon its thermal conductivity as well as its thickness. Therefore, the thinner this material is, the better. This material must also exhibit high breakdown voltage as well as a thermal expansion coefficient close to that of aluminum to prevent bowing or warping during the firing process. Also, the material must sinter at a low temperature, due to aluminum's low melting temperature ($\sim 640-660^{\circ}\text{C}$). Certainly, a dielectric

material which meets all of these requirements must be quite unique.

This paper will discuss the performance of two lead-free thick film pastes on 3003 and 6061 aluminum alloys, as defined by the International Alloy Designation System (IADS). The thermal conductivity of the materials will be compared. The amount of bowing of the substrate will be examined, as well as its dependency on multiple firings and substrate thickness. Dielectric properties will be measured as a means of determining reliability of the materials before and after thermal and environmental testing.

Materials and Substrates

The green and grey versions of the dielectric pastes, CL90-9217 and CL90-9275, were tested. CL90-9275 was printed on 3003 alloy and 6061 alloy. CL90-9217 is printed only on 3003 alloy. The compositions of these alloys are given in Table 1.

The dielectric was printed using a 200 mesh screen with 1.6 mil wire diameter and 0.5 mil emulsion at a print speed of 4 in./sec. Two layers were sequentially fired at 550°C to reach a total fired thickness of 52-58 μm . Heraeus silver conductor CL80-9316 was printed on top with a thickness of 8-10 μm , after firing at 490°C .

Table 1. Composition of aluminum alloys in weight percent. All values are maximum allowed values; there is no minimum unless a range is given. Source www.luskmetals.com.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zi	Ti	Al
3003	0.6	0.7	0.05 - 0.2	1.0 – 1.5	-	-	-	0.1	Remainder
6061	0.4 - 0.8	0.7	0.15 – 0.4	0.15	0.8 – 1.2	0.04-0.35	0.25	0.15	Remainder

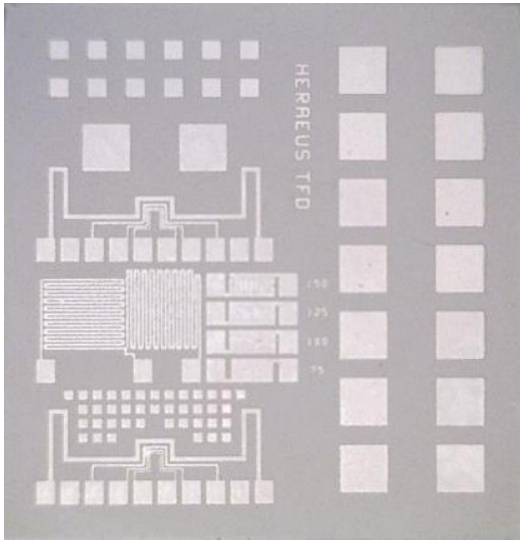


Figure 1. Conductor test pattern; printed overtop CL90-9275

Experimental Procedure

Electrical properties were measured before and after reliability testing. Properties measured include dielectric constant (K), insulation resistance (IR) and dielectric breakdown voltage.

Dielectric Constant (K): Capacitance was measured at 1000 Hz using an ESI Video Bridge 2160 on 200 x 200 mil conductor pads on each dielectric. An average of the dielectric thickness was used in calculation of the K value.

Dielectric Breakdown Voltage: The dielectric strength was measured with a Keithley Instruments 246 High Voltage Source with DC voltage under positive polarity. The voltage was increased at an increment of 100V. Each value was held for 20 seconds before it was increased. Voltage is limited at 3100V due to the limitation of the instrument.

Insulation Resistance: Insulation resistance was measured using a HP 4329A High Resistance Meter, 100V test voltage and a ~20 second charge time.

The parts were subjected to thermal cycling, from -20°C to 80°C for up to 100 cycles. The dwell time was 10 minutes with a 15 minute ramp time. Parts were removed after 30 cycles and 100 cycles. The parts were placed in a dry box for 2 hours to prevent any moisture adsorption while cooling.

Humidity and thermal reliability testing was performed at 85°C in 85% relative humidity. Parts were removed at 24 hours and at 100 hours. Parts were allowed to sit for 2 hours before measurement.

Long term, higher temperature stability was assessed by changes in breakdown voltage. Parts were placed in an oven at 150°C and tested for breakdown voltage after 250 and 1000 hours.

Substrate Bowing: The dependency of bowing on substrate thickness and repeat firings was measured. Thermal mismatch was quantified by measuring the maximum deflection along the edge of a 57mm x 57mm substrate with two sequentially fired dielectric base layers on top (100% coverage). Deflection was measured on three substrate thicknesses: 1.25mm, 1.6mm, and 2mm. After measuring deflection, the substrates were subjected to three additional firings at 550°C.

The deflection was measured with an optical microscope by positioning the aluminum substrate against a straight-edged alumina substrate and measuring the distance between the alumina and the point of greatest deflection. Deflection is reported in $\mu\text{m}/\text{mm}$. This indicates the amount of bowing (in μm) divided by the length of the substrate (in mm) along which the deflection is measured.

Thermal Conductivity: Thermal conductivity (λ) of the insulating layer is determined according to the thermal diffusivity (α), specific heat capacity (C_p) and density of the material (ρ)

$$\lambda = \alpha C_p \rho$$

The thermal diffusivity of 2 fired dielectric layers on a 12.7mm x 12.7mm x 2mm substrates was measured using laser flash diffusivity, ASTM E1461. Specific heat capacity was determined on the inorganic powders of the paste using DSC. The instrument was Netzsch model DSC 204 F1. The calculation of the specific heat follows ASTM E1269.

Solderability and adhesion of the conductor were performed with Sn62/Pb36/Ag2 solder at 225°C. The parts were dipped in α 615 RMA flux for 5 seconds and then dipped for 3-5 seconds in the

solder. Adhesion was measured after soldering Sn/Pb coated Cu leads onto the conductor. The pulls were made using a Zwick pull tester.

Results

The averages listed for each test in this document reflect a sample size of at least 12 measurements, except thermal diffusivity which had 3 samples per substrate-paste combination. The initial sample measurements are consistent across each test; the values are representative of the entire set of parts, not just the parts for that specific test.

Solderability and initial adhesion of the conductor can be seen in Figure 2, which shows the excellent solderability of CL80-9316, obtaining 100% coverage.

For ease of notation on the following figures, the material-substrate combinations will be labeled as follows:

CL90-9275 on 3003 alloy will be "A".

CL90-9275 on 6061 alloy will be "B".

CL90-9217 on 3003 alloy will be "C".

Table 2. Fired thickness, resistivity, adhesion, breakdown voltage (BDV) and insulation resistance (IR) of CL80-9316 with each configuration. *Resistivity is normalized to a 12 μm thickness.

	A	B	C
Conductor ftt (μm)	9.2	9.8	8.5
Resistivity ($\text{m}\Omega/\square$)*	3.026	2.936	2.978
Adhesion (lbs.)	> 4.0	> 4.0	> 4.0
Ave. BDV (VDC)	2938	1743	2678
IR ($\Omega \times 10^9$)	1.2	1.3	0.8

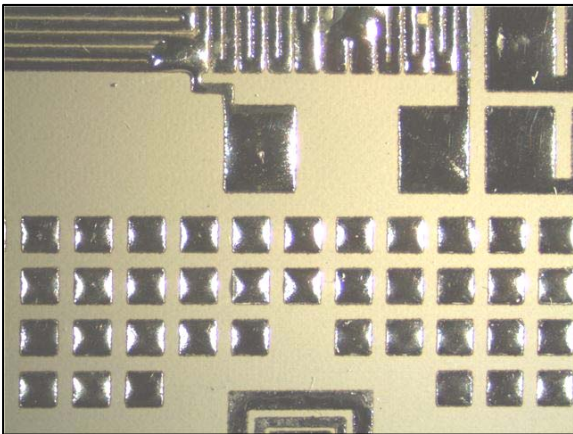


Figure 2. Solderability of CL80-9316 on CL90-9275.

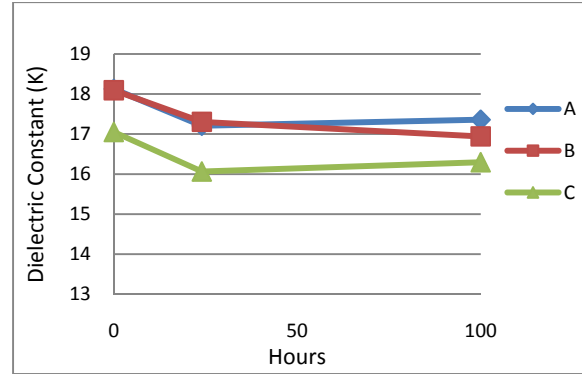


Figure 3A. K value; initial vs. 85°C/85% RH testing.

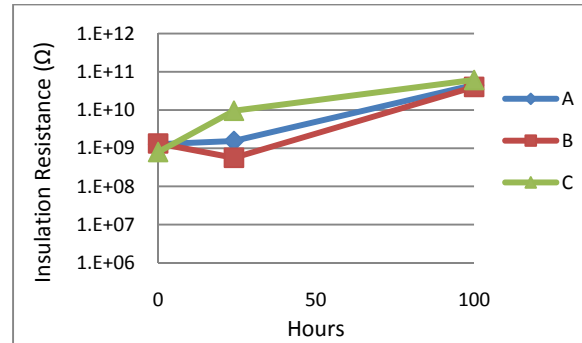


Figure 3B. Insulation resistance (IR); initial vs. 85°C/85% RH testing.

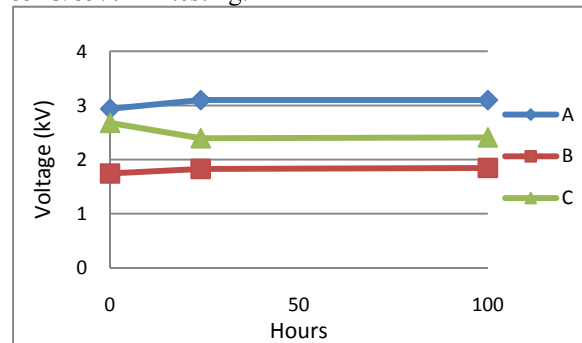


Figure 3C. Dielectric breakdown voltage; initial vs. 85°C/85% RH testing.

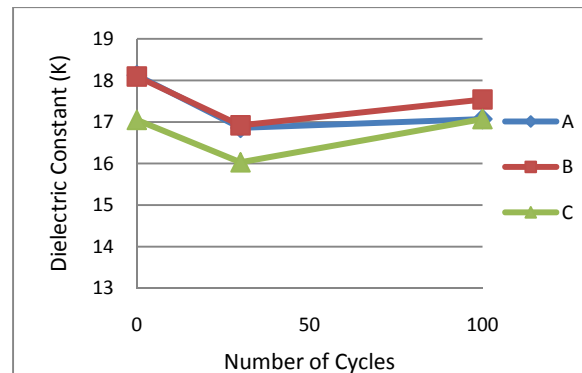


Figure 4A. K Value; initial vs. thermally cycled (-20 to 80°C).

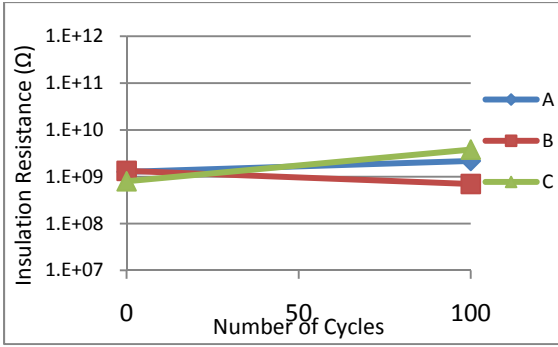


Figure 4B. Insulation resistance (IR); initial vs. thermally cycled (-20 to 80°C).

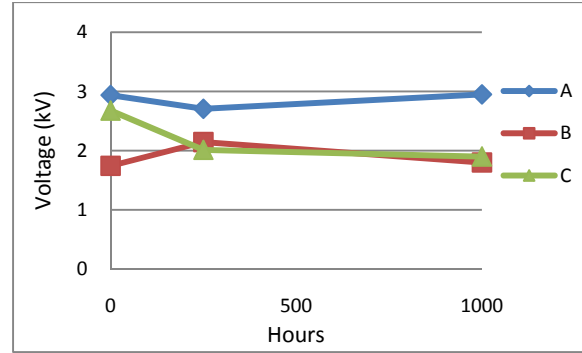


Figure 5. Dielectric breakdown voltage; initial vs. aged @ 150°C.

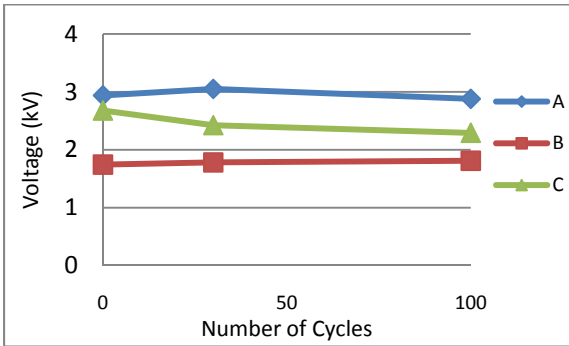


Figure 4C. Dielectric breakdown voltage; initial vs. thermally cycled (-20 to 80°C).

Table 3. Deflection of dielectric substrate combinations (in $\mu\text{m}/\text{mm}$). The unit represents the amount of deflection per unit of substrate length.

	CL90-9275/3003 alloy; A		CL90-9275/6061 alloy; B		CL90-9217/3003 alloy; C	
Substrate thickness	2 Fires	5 Fires	2 Fires	5 Fires	2 Fires	5 Fires
1.25 mm	9.26	22.8	4.42	6.67	6.14	16.22
1.60 mm	4.82	11.49	2.54	3.42	3.42	9.73
2.00 mm	3.24	7.89	1.32	2.02	2.63	5.26

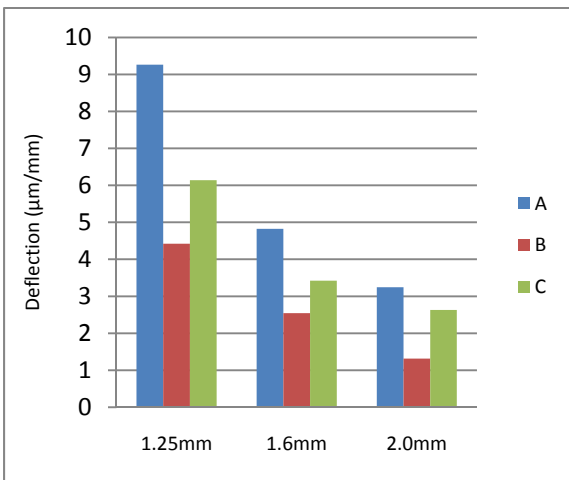


Figure 6A. Deflection per unit length of different aluminum substrate thicknesses after 2 fires (in $\mu\text{m}/\text{mm}$).

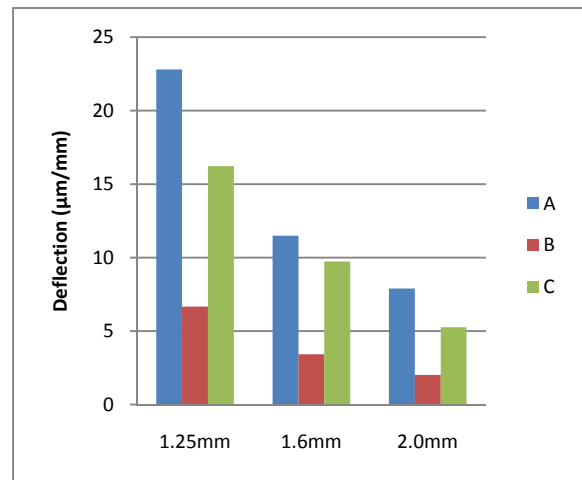


Figure 6B. Deflection per unit length of different aluminum substrate thicknesses after 5 fires (in $\mu\text{m}/\text{mm}$).

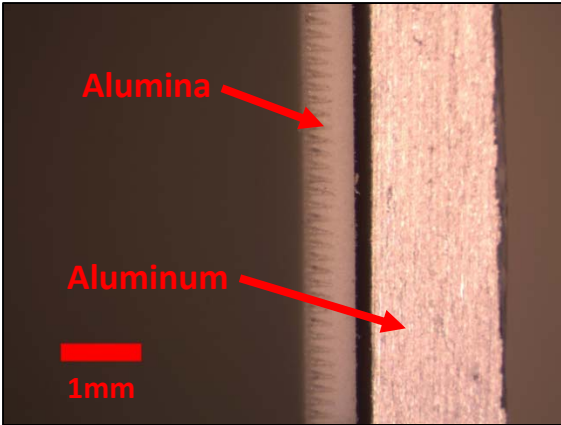


Figure 7A. Microscopic view of the bowing of CL90-9217 on 1.6mm thick 3003 aluminum alloy after 2 fires. (16X)

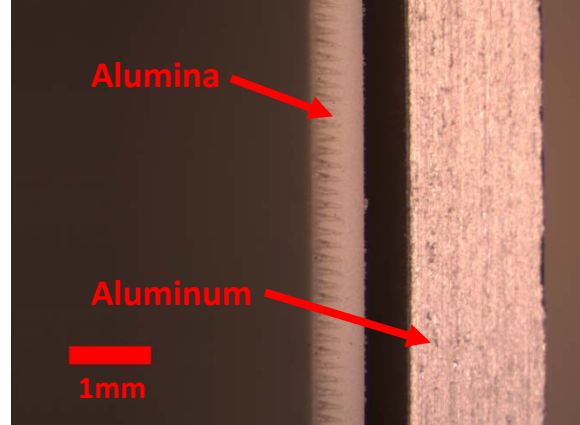


Figure 7B. Microscopic view of the bowing of CL90-9217 on 1.6mm thick 3003 aluminum after 5 fires. (16X)

Table 4. Thermal properties of each dielectric layer @ 25°C.

	Specific Heat (J/g-K)	Bulk Density (g/cm ³)	Thermal Diffusivity (mm ² /s)	Thermal Conductivity (W/m-K)
9275/3003	0.794	3.31	0.765	2.05
9275/6061	0.794	3.31	0.44	1.1
9217/3003	0.824	3.53	0.58	1.71

Discussion

One of the most critical properties of an insulating dielectric is to withstand a high voltage potential between the top conductor and the metal substrate. Initial breakdown voltage for the materials was excellent with CL90-9275 on 3003 being the highest. The prolonged exposure to high humidity or repeated thermal cycling did not have an effect on the breakdown voltages of any of the three samples. High temperature (150°C), long term (1000 hr.) testing shows all materials maintain their initial values with little change.

Developing a ceramic material that closely matches the high thermal expansion coefficient (CTE) of aluminum is certainly a challenge. The glasses used in CL90-9217 and CL90-9275 exhibit a close match so that gross defects, like cracking and delaminations, are not evident. However, the CTE is slightly different which will result in some deflection of the aluminum substrate. The testing shows that after two firings both dielectrics have some minor level of bowing that decreases with increasing substrate thickness. The deflection of the aluminum substrate also increases after repeated firings, as expected. 6061 alloy bows less than 3003 alloy. While bowing of the substrate may cause some concern, proper selection of substrate dimensions, number of refires, and selection of the

appropriate alloy will help to minimize the deflection.

Another critical property is the thermal conductivity of the dielectric material. The testing shows that the thermal performance was greatest on 3003 alloy, with CL90-9275 performing better than CL90-9217 in thermal diffusivity.

The dielectric properties are a measure of the overall robustness and reliability of the thick film coating on aluminum substrates. Major changes in the dielectric properties can indicate deterioration of the materials performance. For both thick film pastes, the dielectric constant (K) and insulation resistance remain consistent across all samples after reliability testing, with only slight deviations. The testing was consistent for both 85°C/85%RH and thermal cycling conditions. Slight variations seen in the data are most likely related to ambient humidity or other variations in testing conditions.

3003 alloy appears to be the best choice of alloy in terms of the dielectric's thermal conductivity, electrical reliability and breakdown voltage, as either paste performs well on it. The absolute breakdown voltage of CL90-9275 must be further investigated, because the reported values are not completely descriptive of the material due to the limited range of the instrument (3100V). Additionally, more work may be required to determine the effect, if any, of the temper of the alloy on bowing.

Conclusion

Two novel thick film dielectric materials have been developed for aluminum substrates. Both materials appear to perform excellent on 3003 alloy with minimal change in performance. CL90-9275 is compatible with both 3003 and 6061 alloys; CL90-9217 is compatible with 3003 alloy. The dielectric properties and breakdown voltage of both materials are stable after reliability testing under 85°C/85%, thermal cycling, and thermal aging. The material offers similar thermal conductivity to a standard metal-core printed circuit board (MCPCB) at about 2 W/m-K. These results demonstrate their suitability

as excellent thermal interface materials on high thermal conductivity aluminum substrates, while providing the design versatility of thick film technology. In addition, the materials maintain simplicity of processing as both are one-part systems; there is no need for a base layer or undercoat layer on the aluminum.

Acknowledgements

The authors would like to thank Caitlin Shahbazi and Ashley Hargrove for their contributions to this project.