Electrical Performance of Co-Fired Alumina Substrates at High Temperatures

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Abstract

A 96% polycrystalline alumina (Al_2O_3) based prototype packaging system with Au thick-film metallization successfully facilitated long term testing of high temperature SiC electronic devices for over 10,000 hours at 500°C previously. However, the 96% Al_2O_3 chip-level packages of this prototype system were not fabricated via a commercial co-fire process which is more suitable for large scale commercial production. The co-fired alumina materials adopted by the packaging industry today usually contain several percent of glass constituents to provide better adhesion and sealing at interfaces formed during a co-firing process at temperatures usually lower than the regular sintering temperature for alumina. In order to answer the question if co-fired alumina substrates can provide reasonable high temperature electrical performance comparable to those of regular 96% alumina sintered at 1700°C, this paper reports on the dielectric performance of a selected high temperature co-fired ceramic (HTCC) alumina substrate and a low temperature co-fired ceramic (LTCC) alumina (polycrystalline aluminum oxides with glass constituents) substrate from room temperature to 550°C at frequencies of 120 Hz, 1 KHz, 10 KHz, 100 KHz, and 1 MHz. Parallel-plate capacitive devices with dielectrics of these co-fired alumina and precious metal electrodes were used for measurement of the dielectric properties of the co-fired alumina materials in the temperature and frequency ranges. The capacitance and AC parallel conductance of these capacitive devices were directly measured by an AC impedance meter, and the dielectric constant and parallel AC conductivity of the dielectric were calculated from the capacitance and conductance measurement results. The temperature and frequency dependent dielectric constant, AC conductivity, and dissipation factor of selected LTCC and HTCC co-fired alumina substrates are presented and compared to those of 96% alumina. Metallization schemes for co-fired alumina for high temperature applications are discussed to address packaging needs for low power 500°C SiC electronics.

Keywords: Co-fired alumina, dielectric properties, high temperature, packaging

I. Introduction

Polycrystalline alumina (Al_2O_3) substrates have been proposed as packaging substrate materials for 500°C silicon carbide (SiC) electronics because of their superior stability and acceptable electrical properties demonstrated at high temperatures. A 96% Al_2O_3 substrate based prototype packaging system [1,2] with Au thick-film metallization [3] was developed to successfully facilitate long term testing of high temperature SiC electronic devices for over 10,000 hours at 500°C in a laboratory environment [4]. The alumina substrate used for this prototype package is 96% alumina sintered at ~1700°C, and the alumina chip-level packages of this prototype system were not fabricated via an integrated commercial co-fire process which is more suitable for large scale commercial production. The co-fired alumina materials adopted by the packaging industry today usually contain several percent of glass constituents to provide better adhesion and sealing at interfaces formed during a co-firing process at temperatures usually lower than the regular sintering temperature for alumina. In order to answer the question if co-fired alumina substrates can provide reasonable high temperature electrical performance comparable to those of regular 96% alumina sintered at 1700°C, this paper reports on the dielectric performance of a selected high temperature co-fired ceramic (HTCC) alumina substrate [5] and a low temperature co-fired ceramic (LTCC) alumina [6] (polycrystalline aluminum oxide with glass constituents) substrate from room temperature to 550°C at frequencies of 120 Hz, 1KHz, 10KHz, 100 KHz, and 1MHz, and discusses a metallization scheme compatible with high temperature co-fired alumina substrates for 500°C packaging applications.

II. Experimental Details

An HTCC 94% alumina substrate and an LTCC alumina substrate acquired from two different mainstream manufacturers were selected and used for this work. A capacitive device for measuring temperature dependent dielectric properties of HTCC alumina substrate was fabricated on a 2.77 cm x 3.88 cm x 1.70 mm (1.09 in. x 1.53 in. x 67 mil) HTCC white color 94% alumina substrate (as the dielectric) with gold (Au) thick-film metallization (used as the two electrodes) on both sides of the substrate. The surface roughness of the substrates was ~ 0.38 μm (15 micro-inch) (rms). The electrode/metallization area was 3.37 cm x 2.32 cm (1.33 in. x 0.91 in.) and located at the center of the substrate. The capacitive device for measuring dielectric properties of the LTCC alumina substrate was fabricated on a 7.0 cm x 7.0 cm x 1.065 mm (2.75 inch x 2.75 inch x 41 mil) LTCC alumina substrate. The electrode/metallization area was 5.25 cm x 5.25 cm (2.067 in. x 2.067 in.) and located at the center of the substrate. Au thick-film material was printed on both HTCC and LTCC substrates and cured at 850°C in air. Au wires with 10 mil diameter were bonded onto the Au electrodes (metallization) areas to electrically connect the capacitive device with measuring instruments via 1 m long coaxial cables. These capacitive devices were thermally soaked in a box oven in which the temperature was controlled to an accuracy of 2°C during the experiment. Prior to data acquisition, the capacitive devices were first heated in 550°C air ambient for 24 hours. The AC impedance of the alumina capacitive devices was measured by an AC impedance meter. Small signal (1 V rms) sinusoidal voltage at frequencies *f* = 120 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz was applied to these capacitive devices. The capacitive device was electrically modeled as a parallel circuit composed of an ideal capacitor (without parasitic self-inductance and conductance) for polarization current and an ideal parallel resistor (without parasitic capacitance and self-inductance) for conduction and dielectric loss current. The dielectric constant of alumina substrate (the dielectric) is calculated from the capacitance at frequency *f*, and effective AC conductivity of the dielectric is calculated from the admittance. With this linear parallel circuit model, the measured complex AC admittance, *Y*, at frequency *f* is a linear function of the relative dielectric constant, ε', and AC effective volume conductivity, σ_{eff}:

$$Y(T,f) = \sigma_{eff}(T,f)A/d + j2\pi f\varepsilon_o\varepsilon'(T,f)A/d \quad (1)$$

where ε_o is the vacuum dielectric constant, *T* is temperature, *A* is electrode area, and *d* is the parallel electrode separation distance (thickness of the Al_2O_3 dielectrics). For the LTCC test device, since $A^{1/2} >> d$ (52.5 mm compared with 1.065 mm) the capacitive boundary effects at metallization edges can be approximately ignored. However, for the HTCC test device, the metallization area is smaller and the dielectric is thicker (23 mm compared with 1.7 mm) so the edge effect is considered [7,8]. The tests were conducted in the temperature range $23^o C \le T \le 550^o C$, and frequencies at 120 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz in this work. $\sigma_{eff}(T, f=0)$ is the DC conductivity. Both the dielectric constant and the effective volume conductance of the dielectric (HTCC alumina or LTCC alumina in our case) can be directly calculated from the measured AC admittance through Equation 1. Typically, σ_{eff} decreases with temperature for good conductors such as metals, while it increases with temperature for semiconductors and good insulators such as ceramics. Ideally, for a packaging substrate material both dielectric constant and conductivity are expected to be low and stable with respect to temperature and frequency so the packaging parasitic effects would be low and stable.

The dissipation Factor *D* of an RC parallel circuit is defined as the ratio of the conductance to the reactance measuring the ratio of the in-phase current (with respect to the voltage source) to the current with a -90° phase shift (with respect to the voltage source):

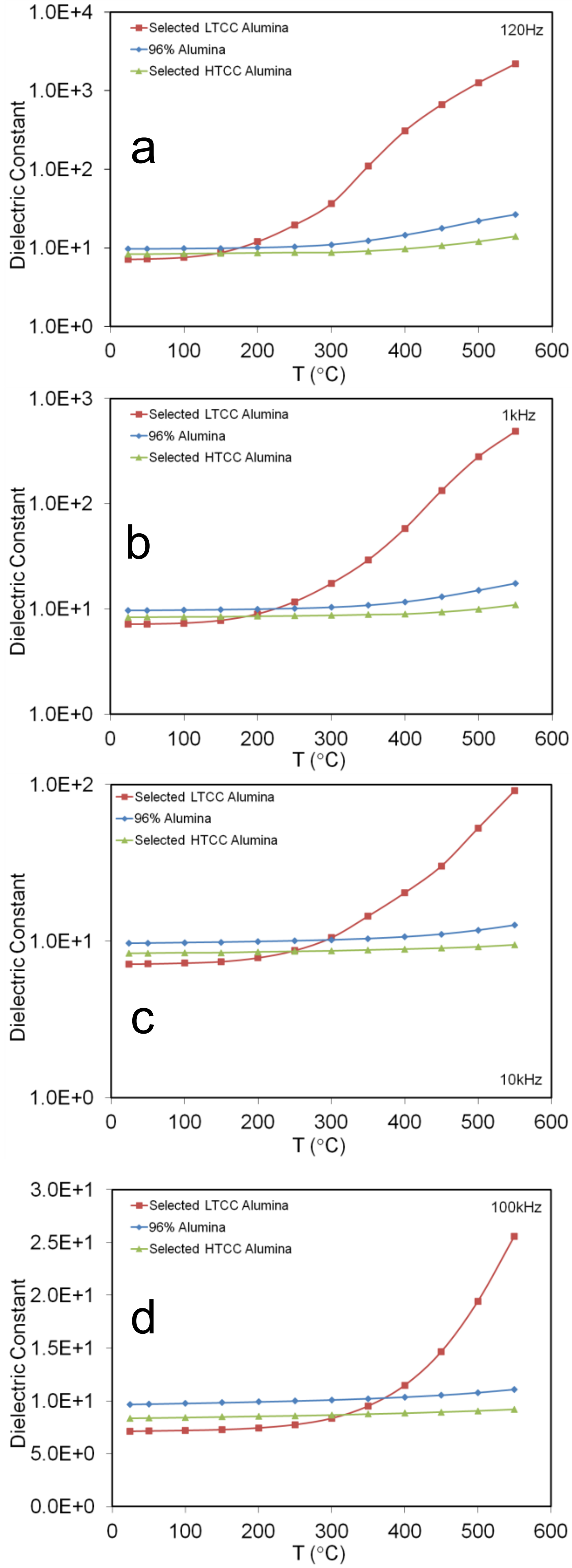
$$D = \sigma_{eff} / 2\pi f\varepsilon' \quad (2)$$

D also measures the ratio of the energy dissipated per cycle to the average energy stored in the capacitor and it is independent of the device (capacitor) dimensions. For an ideal dielectric material, the dissipation factor is expected to be low and stable with respect to temperature and frequency.

III. Results

The dielectric properties of regular 96% alumina with yttrium oxide as firing agent are used as benchmarks to evaluate HTCC and LTCC alumina materials. The regular 96% alumina substrates are fired at ~1700°C. The data of dielectric properties of 96% alumina were measured previously using the same method under the same conditions [9].

The dielectric constants of tested HTCC and LTCC alumina substrates are shown in Figure 1a-e with those of 96% alumina for comparison, between room temperature and 550°C at various frequencies. For HTCC alumina, the dielectric constant at room temperature is 8.4, at all frequencies, compared with 9.7 of 96% alumina. It increases slowly with temperature, although it increases more at lower frequencies. At 550°C, the dielectric constant of the HTCC alumina increases 67.9% to 14.1 at 120 Hz while that of previously tested 96% alumina



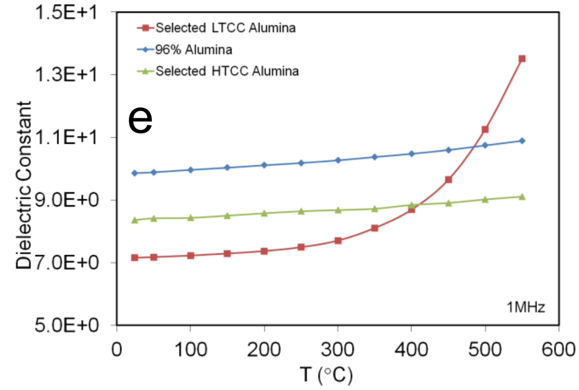
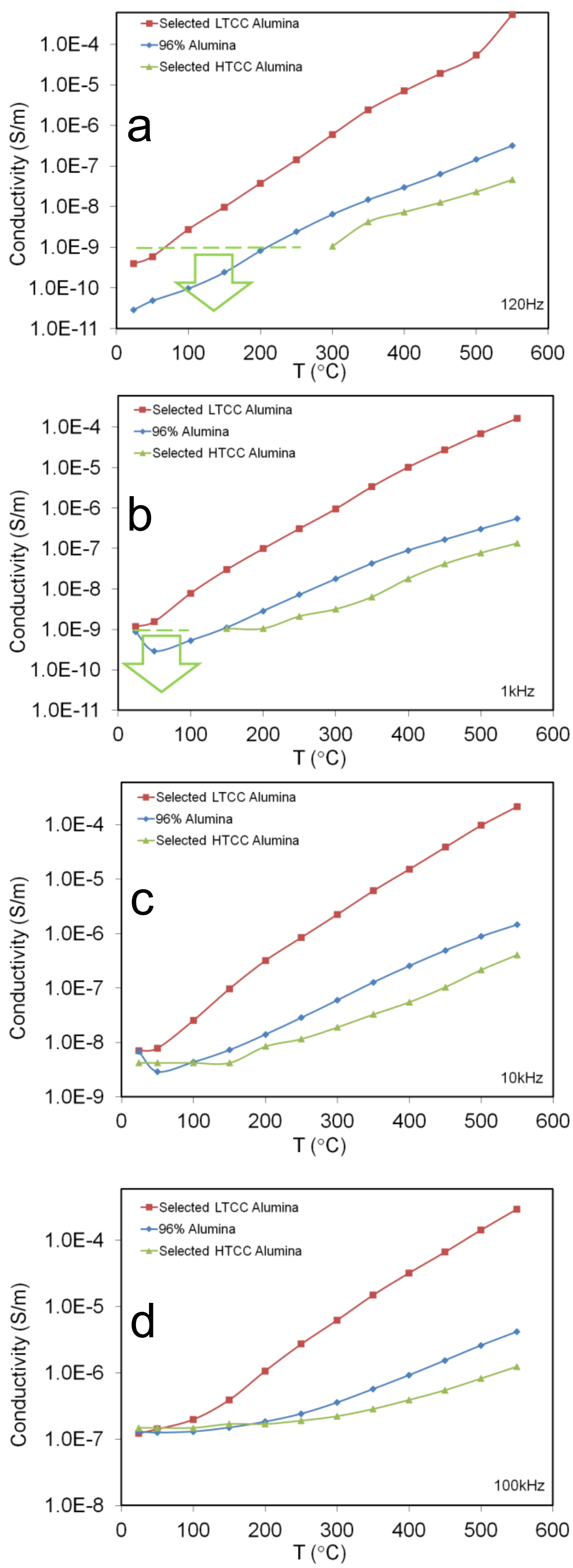


Figure 1: Dielectric constant of HTCC and LTCC alumina substrates, compared with 96% polycrystalline Al_2O_3, between room temperature and 550°C, a) at 120 Hz, b) 1 kHz, c) 10 kHz, d) 100 kHz, and e) 1 MHz. The data of 96% alumina is from Reference [9].

substrate increases 173.6% to 26.54; at 1 kHz, the dielectric constant of HTCC alumina increases 30.2% to 10.94 while that of 96% alumina increases 80.4% to 17.5; at 10 kHz, the dielectric constant of HTCC alumina increases 12.6% to 9.46 while that of 96% alumina increases 30.9% to 12.7. At 100 kHz and 1 MHz, the dielectric constant of HTCC alumina increases 9.4% to 9.19 and 8.3% to 9.10, respectively, while that of 96% alumina increases 14.2% to 11.08 and 12.3% to 10.89, respectively. Overall, the dielectric constant of HTCC alumina is slightly lower than that of 96% alumina, and also changes (increases) less with temperature at high temperatures compared with 96% alumina.

For LTCC alumina, the dielectric constant at room temperature is 7.2, at all frequencies, slightly lower compared with those of HTCC alumina and 96% alumina. It increases rapidly with temperature above 300°C, especially at low frequencies. At 550°C, the dielectric constant of the LTCC alumina increases by a factor of 303 to 2181 at 120 Hz; at 1 kHz, the dielectric constant of LTCC alumina increases by a factor of 67.7 to 487.6; at 10 kHz, it increases by a factor of 12.7 to 91.5. At 100 kHz, the dielectric constant of LTCC alumina increases by a factor of 3.6 to 25.6, much less compared with those at lower frequencies, and at 1 MHz, it increases by a factor of 1.88 to 13.5. Overall, the dielectric constant of LTCC alumina substrate is very high at elevated temperatures, especially above 300°C, at low frequencies.

The conductivity data of tested HTCC and LTCC alumina substrates are shown in Figure 2a-e, with those of 96% alumina tested previously [9] for comparison, between room temperature and 550°C at various frequencies. For HTCC alumina, the conductivity basically increases with temperature. At 120 Hz, the conductivity was not directly measurable due to the limit of sensitivity of the impedance meter



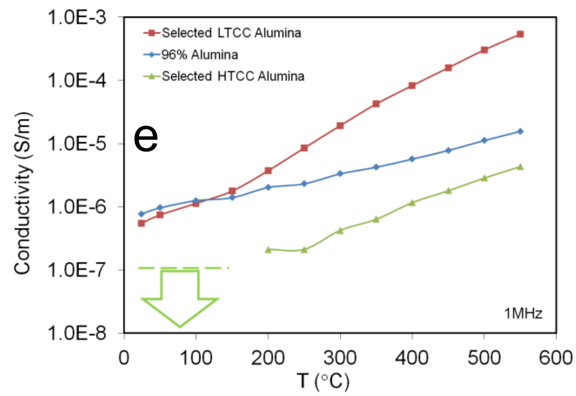


Figure 2: AC conductivity of HTCC and LTCC alumina substrates, compared with 96% polycrystalline Al_2O_3, between room temperature and 550°C, a) at 120 Hz, b) 1 kHz, c) 10 kHz, d) 100 kHz, and e) 1 MHz. The data of 96% alumina is from Reference [9].

and the size of the test device. The conductivity is under 10^{-9} S/m between room temperature and 250°C, it increases with temperature above 300°C and it is 4.65×10^{-8} S/m at 550°C while that of 96% alumina is 3.2×10^{-7} S/m; At 1 kHz, the conductivity was not directly measurable up to 100°C, and it is under 10^{-9} S/m between room temperature and 100°C, the conductivity increases with temperature above 150°C and it is 1.3×10^{-7} S/m at 550°C while that of 96% alumina is 5.5×10^{-7} S/m; At 10kHz, the conductivity is 4.2×10^{-9} S/m between room temperature and 150°C, the conductivity increases with temperature above 150°C and it is 4.1×10^{-7} S/m at 550°C while that of 96% alumina is 1.5×10^{-6} S/m. At 100 kHz, the conductivity of the HTCC alumina is 1.5×10^{-7} S/m between room temperature and 150°C, and above 200°C it increases with temperature to 1.3×10^{-6} S/m at 550°C while that of 96% alumina is 4.2×10^{-6} S/m. At 1 MHz, the conductivity was not directly measurable again due to the limit of the meter sensitivity and sample size at temperatures below 200°C (the upper limit assessed using the instrument sensitivity is less than 10^{-7} S/m), it increases from 2.1×10^{-7} S/m at 200°C to 4.3×10^{-6} S/m while that of 96% alumina increases from 2.0×10^{-6} S/m at 200°C to 1.6×10^{-5} S/m at 550°C. Overall, at temperatures above 200°C the conductivity of HTCC alumina is lower than that of 96% alumina at all frequencies tested.

For LTCC alumina, the conductivity at room temperature and 120 Hz is 3.9×10^{-10} S/m, about an order of magnitude higher than that (2.9×10^{-11} S/m) of 96% alumina, but at all other frequencies, the conductivity of LTCC at room temperature is very close to that of 96% alumina. The conductivity of the LTCC alumina increases rapidly with temperature at all frequencies, especially, above 300°C. At elevated temperatures, the conductivity of LTCC alumina is basically higher than that of 96% alumina at all testing frequencies. At 550°C, the conductivity at 120 Hz is 5.4x10^{-4} S/m, it is higher than that of 96% alumina by more than two orders of magnitude; at 1 kHz, it is 1.6x10^{-4} S/m; at 10 kHz it is 2.2x10^{-4} S/m; at 100 kHz the conductivity is 3.0x10^{-4} S/m, and at 1 MHz it is 5.4x10^{-4} S/m. So overall, the AC conductivity of this LTCC alumina is much higher than that of 96% alumina and HTCC alumina. The conductivity of LTCC alumina starts to increase more rapidly at temperatures ~ 300°C at all frequencies, this would be more obvious if the conductivity vs. temperature data were plotted in linear scale (not shown).

The dissipation factors of the LTCC alumina, 96% alumina, and the HTCC alumina are shown in Figure 3a-c. Basically, dissipation factors of all three materials increase rapidly with temperature above 50°C. Between room temperature and 50°C the conductivity of 96% alumina, at 1 kHz and 10 kHz, decreases with temperature so the dissipation factor of 96% alumina at these frequencies actually decreases slightly with temperature. For LTCC alumina, above 100°C the dissipation factor decreases monotonically with frequency. The dissipation factor of the 96% alumina decreases monotonically with frequency above 250°C. The dissipation factor of HTCC decreases monotonically with frequency above 350°C. Compared with 96% alumina, the dissipation factor of LTCC alumina is always higher at temperatures above 100°C, while that of HTCC alumina is always lower compared with that of 96% alumina at temperatures above 250°C.

IV. Discussion

LTCC alumina is a material system with many advantages, such as low processing temperature, multi-layer capability, availability of many choices of highly conductive metallization, low cost, and possibility of on-board integration with passive components such as resistors and capacitors. The temperature dependence of dielectric properties of the tested LTCC alumina is very similar to those of low purity alumina [10]. Both dielectric constant and AC conductivity of the material increase with temperature rapidly above 300°C, especially at low frequencies. So this material is more suitable for the temperature range below 350°C with moderate packaging density.

Compared with LTCC alumina, HTCC alumina may provide better hermeticity. Compared with 96% alumina, the dielectric performance of the tested HTCC alumina are better at elevated

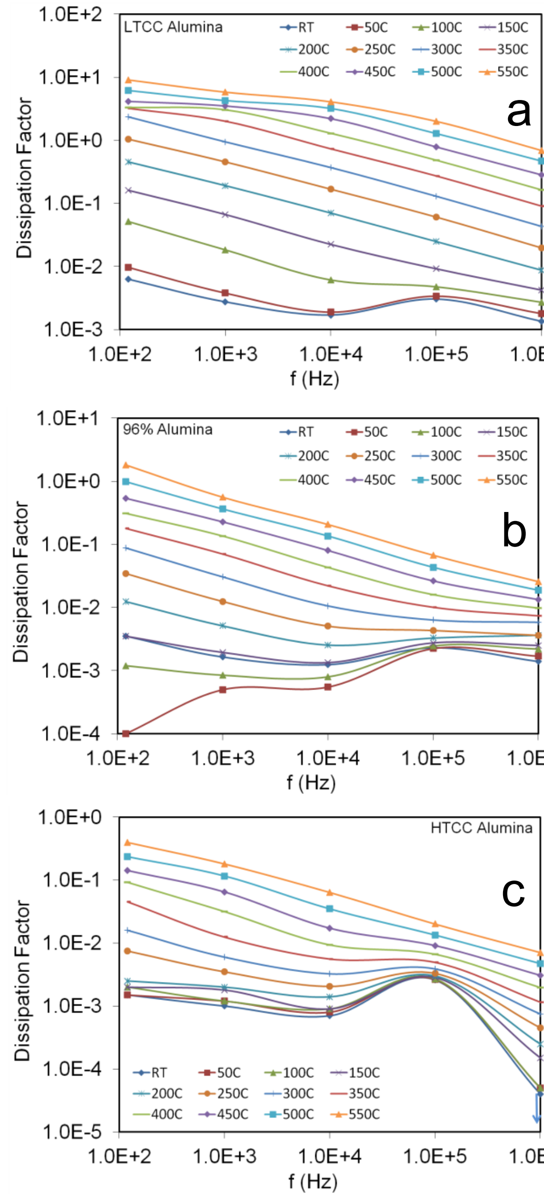


Figure 3: Dissipation factors of (a) LTCC, (b) 96% polycrystalline Al_2O_3, and (c) HTCC alumina substrates compared, between room temperature and 550°C, at 120 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz. The data of 96% alumina is from Reference [9].

temperatures. Overall, the dielectric constant is slightly lower and it changes less with temperature. The AC conductivity (dielectric loss) of this material is also lower than that of 96% alumina at temperatures above 200°C, so it is suitable for high temperature applications. HTCC alumina material systems are usually co-fired with thick-film metallization at temperatures ~1600°C in noble environment, and more often only metals with low

CTE (thermal expansion coefficient) such as tungsten and molymanganese are used with HTCC alumina. However, these conventional metal/alloys have relatively high electrical resistivity, and oxidation issues for long term operation in high temperature air ambient. Platinum (Pt) thick-film materials designed for HTCC alumina substrates are more suitable for 500°C packaging applications. Aluminum oxide is usually used as the binder for high temperature thick-film materials designed for HTCC alumina substrates. Alumina-alumina bonds at thick-film/substrate interface are expected to be thermodynamically stable in a wide temperature range. An over-layer of gold, either thin-film or thick-film, on Pt metallization surface may provide the material compatibility needed for gold wire-bonding, as well as gold and gold alloy based die-attach.

There are many types of co-fired alumina materials available on the market, the dielectric properties of these two HTCC and LTCC alumina substrates tested in this article may not represent all of these types of co-fired alumina materials because of different glass additives used for different products. Further testing using more LTCC and HTCC alumina are planned for future work in this direction to further down select the optimal substrate/metallization system for 500°C applications.

Acknowledgement

The author wants to thank Drs. Lawrence G. Matus, Carl W. Chang, Mary V. Zeller, and Gary T. Seng for proof-reading the article. This work was supported by Vehicle Safety System Technology (VSST) project of NASA Aviation Safety Program under NASA Aeronautics NRA grant NNC07ZA11A monitored by Dr. Gary W. Hunter.

Reference

[1] L.-Y. Chen and J.-F. Lei, “Packaging of Harsh Environment MEMS Devices” in: MEMS Design and Fabrication, edited by M. Gad-el-Hak, CRC Press, Boca Raton, Florida, 2006, p.12-1.

[2] L.-Y. Chen, D.J. Spry, and P.G. Neudeck, “Demonstration of 500°C AC Amplifier Based on SiC MESFET and Ceramic Packaging” in: Proc. 2006 iMAPS (International Microelectronics and Packaging Society, Washington, DC) International High Temperature Electronics Conference (2006 HiTEC), Santa Fe, NM, 2006, p. 240.

[3] J.S. Salmon, R.W. Johnson, and M. Palmer, (1998) “Thick Film Hybrid Packaging Techniques for 500°C Operation,” in Trans. Fourth Int. High Temperature Electronics Conf. (HiTEC), June 15-19, Albuquerque, NM.

[4] P.G. Neudeck, S.L. Garverick, D.J. Spry, L.-Y. Chen, G.M. Beheim, M.J. Krasowski, and M. Mehregany, “Extreme Temperature 6H-SiC JFET Integrated Circuit Technology,” Phys. Status Solidi A, 1-17, 2009.

[5] http://www.hccindustries.com/

[6] http://www2.dupont.com/

[7] F. Thompson and J.K. Gagon, “Fringe Capacitance of a Parallel-Plate Capacitor,” Phys. Educ., Vol 17, 1982.

[8] http://chemandy.com/calculators/rectangular-capacitor-calculator.htm

[9] L.-Y. Chen and G.W. Hunter, "Temperature Dependent Dielectric Properties of Polycrystalline 96%A1203 Substrate," Proceedings of Symposium G (Materials, Integration, and Packaging Issues for High-Frequency Devices II), 2004 MRS Fall Meeting, Boston, MA, November 2004.

[10] L.-Y. Chen, “Temperature Dependent Dielectric Properties of Polycrystalline Aluminum Oxide Substrates with Various Impurities,” in Proceedings of 2007 8th International Conference on Electronics Packaging Technology, Shanghai, China, Aug. 14-17, 2007.