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Electrical Performance of Cofired Alumina Substrates at High Temperatures

Liang-Yu Chen

***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 h at 500°C previously. However, the 96% Al_2O_3 chip-level packages of this prototype system were not fabricated via a commercial cofire process, which would be more suitable for large scale commercial production. The cofired alumina materials adopted by the packaging industry today usually contain several percent of glass constituents to allow cofiring processes at temperatures usually lower than the regular sintering temperature for alumina. In order to answer the question of whether cofired alumina substrates can provide a reasonable high temperature electrical performance comparable to regular 96% alumina sintered at 1700°C, this paper reports on the dielectric performance of a selected high temperature cofired ceramic (HTCC) alumina substrate and a low temperature cofired 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 cofired alumina and precious metal electrodes were used for measurement of the dielectric properties of the cofired 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 cofired alumina substrates are presented and compared with those of 96% alumina. Metallization schemes for cofired alumina for high temperature applications are discussed to address the packaging needs for low-power 500°C SiC electronics.**

***Keywords*—Cofired alumina, dielectric properties, high temperature, packaging**

INTRODUCTION

Polycrystalline alumina (Al_2O_3) materials are widely used as packaging substrates for conventional microelectronics because of their excellent electrical properties [1]. More recently, alumina materials 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 [2, 3] with Au thick-film metallization [4] was developed to successfully facilitate long term testing of high temperature SiC electronic devices for over 10,000 h at 500°C in a laboratory environment [5]. The parasitic parameters between neighboring I/Os (inputs/outputs) of this package have been characterized at temperatures up to 550°C, and frequencies up to 1 MHz [6]. The alumina substrate used for this prototype package was 96% alumina sintered at 1700°C, and the alumina chip-level packages of this prototype system were composed of four layers of metalized 96% alumina substrates. These prototype packages were not fabricated via an integrated commercial cofire process, which would be more suitable for large scale commercial production in comparison with those prototype packages integrated in a laboratory. The cofired alumina materials adopted by the packaging industry today usually contain several percent of glass constituents to allow cofiring processes at temperatures usually lower than the regular sintering temperature for alumina. In order to answer the question of whether cofired alumina substrates can provide a reasonable high temperature electrical performance, comparable to that of regular 96% alumina sintered at 1700°C, this paper reports on the dielectric performance of a selected high temperature cofired ceramic (HTCC) alumina substrate [7] and a low temperature cofired ceramic (LTCC) alumina [8] (polycrystalline aluminum oxide with glass constituents) substrate from room temperature to 550°C at frequencies of 120 Hz, 1 KHz, 10 KHz, 100 KHz, and 1 MHz, and discusses a metallization scheme compatible with high temperature cofired alumina substrates for 500°C packaging applications. A packaging substrate material with lower dielectric constant and dielectric loss generates less undesirable parasitic effects, such as parasitic capacitance and leakage between the neighboring I/Os of a chip-level package.

EXPERIMENTAL DETAILS

An HTCC 92% alumina substrate and an LTCC alumina substrate acquired from two different mainstream manufacturers were selected and used for this work. The HTCC 92% alumina includes 8% of glass mainly composed of silicon, oxygen, calcium, and magnesium. The LTCC alumina includes up to 60% alumina, and added glass/ceramic ingredients include boron, calcium, lanthanum, phosphorous, and oxygen. A capacitive device for measuring temperature dependent dielectric properties of HTCC alumina substrate was fabricated on a

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Ohio Aerospace Institute/NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135
email: Liangyu.Chen@grc.nasa.gov

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2.77 cm × 3.88 cm × 1.70 mm (1.09 in. × 1.53 in. × 67 mil) HTCC white color 92% alumina substrate (as the dielectric) with gold (Au) thick-film metallization (used as the two electrodes) on both sides of the substrate. The substrate was prepared by the manufacturer. Multiple layers of the green tape materials were laminated together, and then were fired at 1600°C (in this case without any conductor). The surface roughness of the substrates was about 0.38 μm (15 μin.) (rms). The electrode/metallization area was 3.37 cm × 2.32 cm (1.33 in. × 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 × 7.0 cm × 1.065 mm (2.75 inch × 2.75 inch × 41 mil) LTCC alumina substrate. The substrate was prepared by the material manufacturer, and the green tape materials were laminated together and then fired at 850°C (in this case without any conductor). The electrode/metallization area was 5.25 cm × 5.25 cm (2.067 in. × 2.067 in.) and located at the center of the substrate. Au thick-film material was printed on both HTCC and LTCC substrates and fired 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 ambient air for 24 h to facilitate measurements being more precisely repeatable. The AC impedance of the alumina capacitive devices was measured by an AC impedance meter (HP 4192A and Keithley 3322). Small signal (1 V rms) sinusoidal voltage at frequencies of $f = 120$ Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz were applied to these capacitive devices. The impedance meter was calibrated (short and open) with a 1-m-long coaxial cable to compensate for the impedances of the cable. The AUTO mode of the impedance meter was used to select/verify that the RC parallel circuit model was suitable to the dielectric. The AC impedance of a capacitive device is usually composed of impedances of interconnectors (wires), metal/dielectric interfacial contact, and the dielectric material in series [9]. For a parallel plate capacitive device with high capacitance, at low frequencies, the interconnector (wires) impedance is much lower compared with that of the dielectric material. In case of devices with a thin dielectric, such as capacitors based on thick film and a thin layer of cofired-ceramic dielectric, the contact impedance can be comparable to that of dielectric [9, 10]. However, since the dielectric materials studied in this work are relatively thick and demonstrate reasonably high impedance in the temperature and frequency ranges, therefore, only the dielectric impedance is considered for these capacitive devices; and the circuit is electrically modeled approximately 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. At elevated temperatures, the ion mobility increases with temperature, and the ionic effect on the impedance of a ceramic dielectric is modeled as a frequency-dependent constant phase element [10, 11]. In this work, the contribution of this constant phase element to the impedance of the dielectric is considered by assuming that both effective AC conductivity and effective dielectric constant are frequency- and temperature-dependent. With these discussions, the dielectric constant of alumina substrate (the dielectric) is calculated from the capacitance measurement at frequency f, and the effective AC conductivity of the dielectric is calculated from the admittance measurement. 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 the AC effective volume conductivity, σ_{eff},

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

where ε_o is the vacuum dielectric constant, T is the temperature, A is the electrode area, and d is the parallel electrode separation distance (i.e., the thickness of the Al_2O_3 dielectrics). For the LTCC test device, since $A^{1/2} >> d$ (52.5 mm wide compared with 1.065 mm thick) the capacitive boundary effects at the metallization edges can be approximately ignored. However, for the HTCC test device, the metallization area is relatively smaller and the dielectric is relatively thicker (23.2 mm wide compared with 1.7 mm thick), so the edge effect is considered [12, 13], in order to make the calculated dielectric constant be more accurate. The consideration of edge effect introduces a constant factor of 0.88 to the dielectric constant of HTCC alumina. The tests were conducted in the temperature range of $23°C \le T \le 550°C$ and frequencies of 120 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz. $\sigma_{\mathrm{eff}}\,(T, f = 0)$ 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 eq. (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 (tan δ) 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)

$$D = \frac{\sigma_{eff}}{2\pi f\,\varepsilon_o\varepsilon'} \qquad (2)$$

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.

RESULTS

The dielectric properties of regular 96% alumina substrate with yttrium oxide as the firing agent are used as benchmarks to evaluate HTCC and LTCC alumina materials. The previously measured results of dielectric properties of 96% alumina at room temperature are in the range of those reported elsewhere

[1, 14]. The regular 96% alumina substrates were fired at about 1700°C. The data of dielectric properties of 96% alumina were measured previously using the same method under the same conditions [15]. The dimensions of 96% alumina dielectric were 88.9 mm × 88.9 mm × 0.381 mm, and the Au electrode area was 63.5 mm × 63.5 mm at the center region of the substrate.

The dielectric constants of tested HTCC and LTCC alumina substrates are shown in Figs. 1a-e with those of 96% alumina for comparison, between room temperature and 550°C at various frequencies (these figures are not at the same scale). For HTCC alumina, the dielectric constant at room temperature is 8.4, at all frequencies, compared with 9.7 for 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 whereas that of previously tested 96% alumina substrate increases 173.6% to 26.54; at 1 kHz, the dielectric constant of HTCC alumina increases 30.2% to 10.94 whereas 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 whereas 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, whereas 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

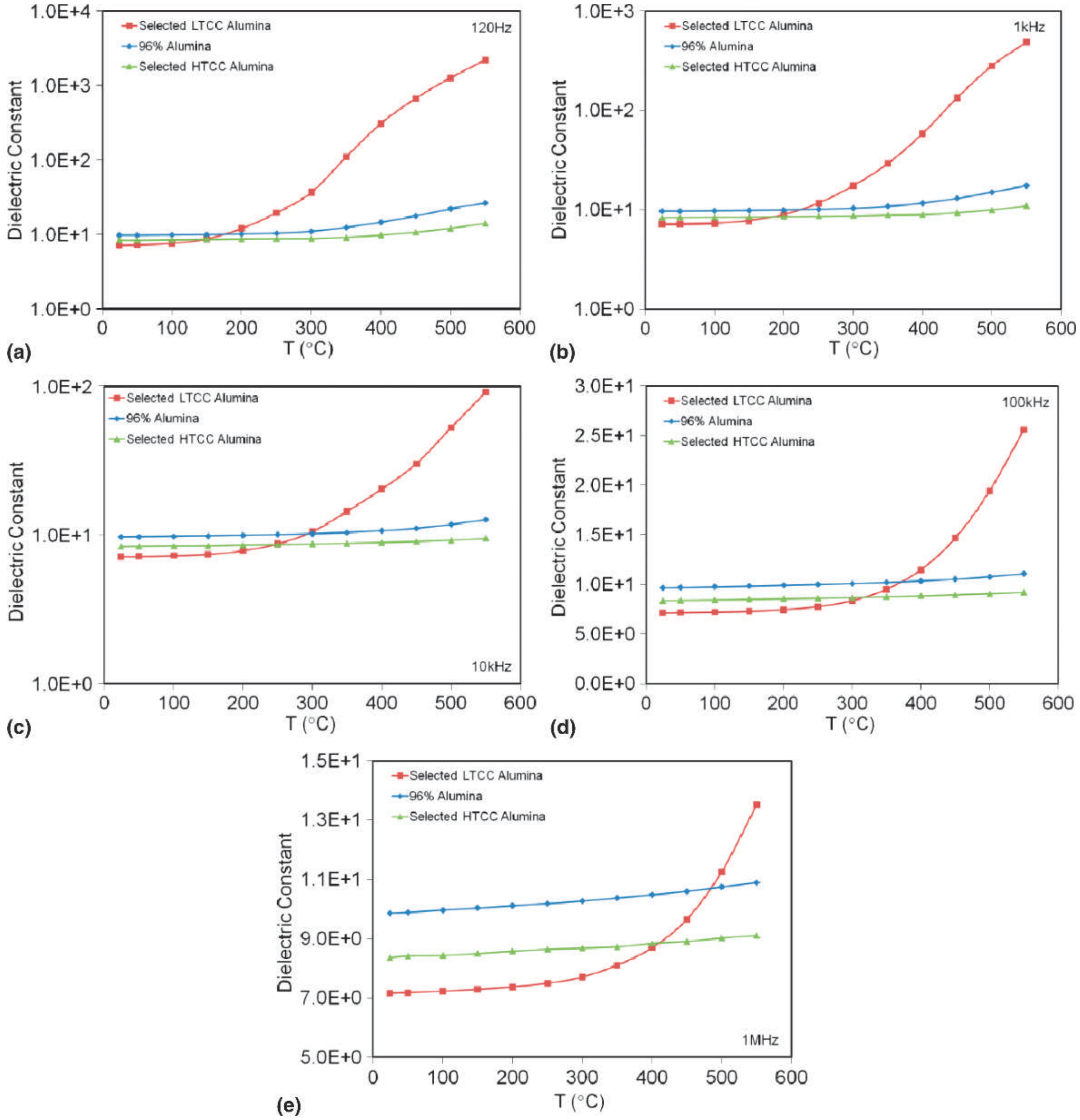

Fig. 1. Dielectric constant of HTCC and LTCC alumina substrates, compared with 96% polycrystalline Al_2O_3 between room temperature and 550°C, (a) 120 Hz, (b) 1 kHz, (c) 10 kHz, (d) 100 kHz, and (e) 1 MHz. The 96% alumina data is from Ref. [15].

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 303-2181 at 120 Hz; at 1 kHz, the dielectric constant of LTCC alumina increases by a factor of 67.7-487.6; at 10 kHz, it increases by a factor of 12.7-91.5. At 100 kHz, the dielectric constant of LTCC alumina increases by a factor of 3.6-25.6, much less compared with those at lower frequencies, and at 1 MHz, it increases by a factor of 1.88-13.5. 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 Figs. 2a-e, with those of 96% alumina tested previously [15] for comparison, between room temperature and 550°C at various frequencies (these figures are not at the same scale). For HTCC alumina, the conductivity increases with temperature. At 120 Hz, the conductivity was not directly measurable due to the limit of sensitivity of the impedance meter 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 10 kHz, 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

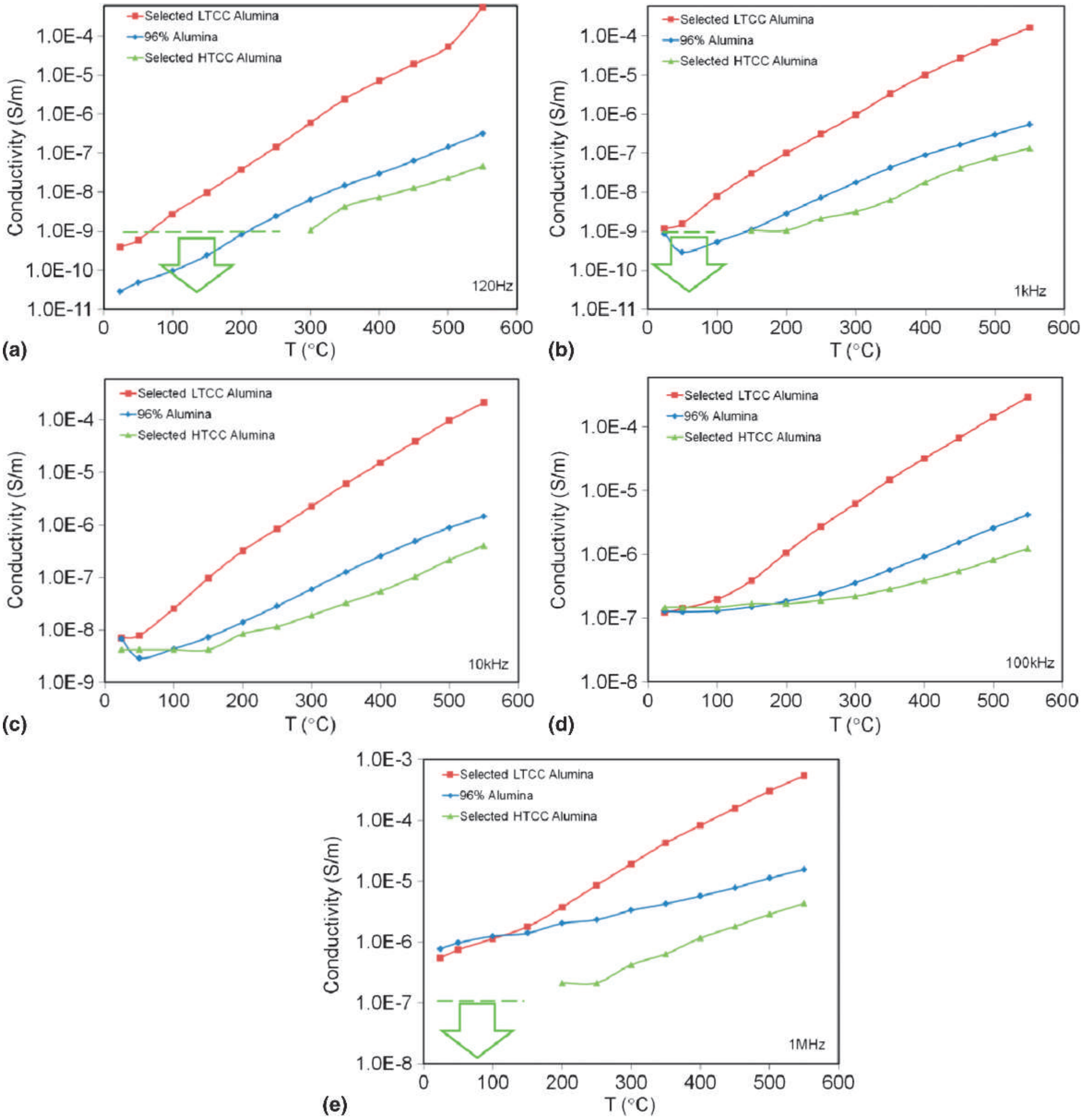

Fig. 2. AC conductivity of HTCC and LTCC alumina substrates, compared with 96% polycrystalline Al_2O_3, between room temperature and 550°C, (a) 120 Hz, (b) 1 kHz, (c) 10 kHz, (d) 100 kHz, and (e) 1 MHz. The data of 96% alumina is from Ref. [15].

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 5.4×10^{-4} S/m, it is higher than that of 96% alumina by more than two orders of magnitude; at 1 kHz, it is 1.6×10^{-4} S/m; at 10 kHz it is 2.2×10^{-4} S/m; at 100 kHz the conductivity is 3.0×10^{-4} S/m, and at 1 MHz it is 5.4×10^{-4} S/m. Thus 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 about 300°C at all frequencies; this would be more obvious if the conductivity versus temperature data were plotted at a linear scale (not shown).

The dissipation factors of the LTCC alumina, 96% alumina, and the HTCC alumina are shown in Figs. 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.

Discussion

LTCC alumina is a material system with many advantages, such as low processing temperature, multilayer 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 [16]. Both dielectric constant and AC conductivity of the material increase with temperature rapidly above 300°C, especially at low frequencies. Thus, this material is more suitable for the temperature range below 350°C with moderate packaging density.

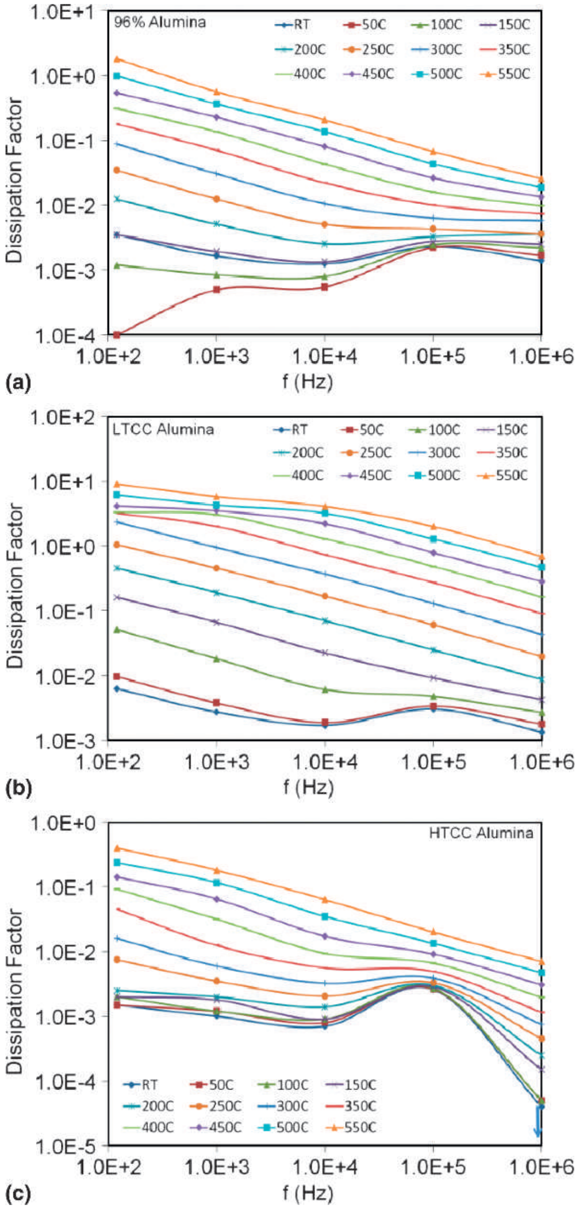

Fig. 3. Dissipation factors of (a) LTCC, (b) 96% polycrystalline Al_2O_3, and (c) HTCC alumina substrates compared, between room temperature and 550°C, at 120 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz. The 96% alumina data is from Ref. [15]. These figures are not at the same scale.

Compared with 96% alumina, the dielectric performance of the tested HTCC alumina is better at elevated 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 cofired with thick-film metallization at temperatures about 1600°C in a noble environment, and more often only metals with low CTE (coefficient of thermal expansion) such as tungsten and moly manganese 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. 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 the Pt metallization surface may provide the material compatibility needed for gold wire-bonding, as well as gold and gold alloy based die-attach.

The difference in dielectric performance of these alumina materials results from the different chemical compositions and electronic structures of these materials. The detailed physical mechanisms of the temperature dependence of dielectric properties of polycrystalline metal oxides with glass additive can be complicated, and need to be further explored.

There are many types of cofired alumina materials (with different chemical compositions) 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 cofired 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.

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