Al_2O_3/glass/hBN composites with high thermal conductivity and low dielectric constant for low temperature cofired ceramic applications

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ABSTRACT

Al_2O_3/glass/hBN composites were successfully fabricated for the LTCC applications. Alignment and homogeneous distribution of the platelet hBN particles during tape casting allowed high hBN (5 wt%) loading as well as facilitated densification at 800°C (density of 2.65 g/cm³, apparent porosity of 0.7%). XRD results proved that hBN neither chemically reacted with the other phases nor decomposed with temperature, which was critical to increase thermal conductivity and at the same time to decrease dielectric constant. Dielectric constant of the dense composites decreased (or, alternatively, enhanced) with increasing hBN content from 7.3 for the 0 wt% hBN to 6.55 for the 5 wt% hBN at 5 MHz. In addition, hBN addition strongly improved the mean thermal conductivity from 1.86 W/m·K for the 0 wt% hBN to 2.43 W/m·K for the 5 wt% hBN between 75°C and 250°C. Therefore, the hBN phase effectively optimized both dielectric and thermal properties at the same time and made the Al_2O_3/glass/hBN composites a promising candidate for the LTCC applications.

1. Introduction

Thin, lightweight and multifunctional electronic components are attracting considerable attention due to the rapid growth of wireless communication systems and microwave devices such as those used in the automotive, medical and telecommunication. Low temperature co-fired ceramic (LTCC) technology allows manufacturing of 3D ceramic modules with embedded components and metal electrodes [1,2]. Glass/ceramic composites are widely used in the LTCC applications due to having some optimized mechanical, dielectric and thermal properties such as low-temperature densification (<950°C) to apply common electrode material (e.g. silver that melts at 961°C), low dielectric loss (0.0007–0.006 at 1 MHz) and low dielectric constant (3.8–9.2 at 1 MHz) to control signal propagation delay, good thermal conductivity (2.0–4.5 W/m·K) to dissipate heat, a matched thermal expansion coefficient (4.5–7.5 ppm/K) to silicon semiconductor to prevent or minimize thermal stress damage and high strength (Young’s modulus of 80–150 GPa, flexural strength of 116–320 MPa) for more efficient and reliable packaging [1]. Addition of low melting glasses has been adopted to lower densification temperature and to optimize physical properties. Luo et al. [3] investigated CaO-Al_2O_3–B_2O_3–SiO_2 glass/Al_2O_3 composites and reported that Al_2O_3/50 wt% glass was fully densified at 875°C and had a dielectric constant (loss) of 8.06 (0.0012) at 7 GHz and a thermal conductivity of 3.1 W/m·K. Li et al. [4] densified CaO-Al_2O_3–SiO_2 glass-ceramic at 850°C and reported a dielectric constant (loss) of 5.5 (0.002) at 1 MHz. Luo et al. [5] studied the effect of CaO on CaO–Al_2O_3–B_2O_3–SiO_2 glass/Al_2O_3 composites produced by the tape casting method. The composites with 9 wt% CaO sintered at 850°C had a dielectric constant (loss) of 7.99 (0.0018) at 7 GHz. Ren et al. [6] reported a dense CaO–Al_2O_3–B_2O_3–SiO_2 glass (Ca/Mg = 4.30)/Al_2O_3 composite with anorthite crystallization after sintering at 875°C. The composite had a dielectric constant (loss) of 8.02 (0.0011) at 10 MHz and a mean thermal conductivity of 2.63 W/m·K between 25°C and 200°C.

Hexagonal boron nitride (hBN) is an important material in terms of its high thermal conductivity (59 W/m·K parallel and 33 W/m·K perpendicular to basal plane at 25°C [7], an averaged thermal conductivity of 33.5 W/m·K at 25°C [8], 20.4 W/m·K (parallel to hot-press direction) and 110.57 W/m·K (perpendicular to hot-press direction) in textured hBN/CaO-Y_2O_3-Al_2O_3 [9]) and very low thermal expansion coefficient (1 ppm/°C along the a/b axis, 4.1 ppm/°C along the c axis) and low dielectric constant (4–4.4 at 1 MHz [7,10], 4.5 and dielectric loss = 0.0003 at 1–10 GHz [11]). hBN is often used as an additive to modify thermomechanical and dielectric properties [12]. Li et al. [13] added 10.3 wt% and 50 wt% hBN to barium aluminosilicate (BAS) and increased thermal conductivity from 2.6 to 7.2 W/m·K at 100°C. Hong et al. [14] studied densification and dielectric properties of calcium
aluminoborosilicate glass with AlN, BN, and Si₃N₄ filler additions. AlN and Si₃N₄ additions favored anorthite crystallization after 850°C, as contrary to BN that initiated no anorthite crystallization even at 1050°C. A dense sample with 30 wt% AlN was produced at 850°C and had a dielectric constant (loss) of ~7.2 (~0.003) at 1 MHz. Highly porous samples with BN and Si₃N₄ fillers had much lower dielectric constants due to insufficient densification.

In our previous study [15], 20 to 60 wt% glass (CaO-SiO₂-Al₂O₃ based)/Al₂O₃ composites were studied for functional (e.g., LTCC) and structural (e.g., radome) applications. As the glass ratio was increased, the sintering temperature decreased from 1350°C for the 20 wt% glass to 850°C for the 60 wt% glass. Also, the dielectric constant decreased with increasing glass ratio from 8.76 (20 wt% glass) to 7.32 (60 wt% glass) at 5 MHz. However, the composite with 60 wt% glass, suitable for the LTCC, had a low thermal conductivity of 0.98 W/m·K at 75°C (and a mean value of 1.23 W/ m·K between 75°C and 250°C). In this study, platelet hBN was added at various ratios from 1 to 10 wt% in order to increase thermal conductivity and at the same time to decrease dielectric constant, which is strongly required for the LTCC applications. hBN was particularly selected for a dual purpose due to its high thermal conductivity and low dielectric constant. To the best of our knowledge, hBN/(CaO-SiO₂-Al₂O₃ based) glass/Al₂O₃ composites have not been reported in the literature. Densification, phase formation, microstructural development, thermal and dielectric properties of the composites were investigated and compared with the literature and commercial products.

2. Materials and methods

Alumina (Al₂O₃, purity 99.78%, Almatis, CT 3000 SG), commercial glass (CaO-Al₂O₃-SiO₂ based; Gizem Fitir, Turkey) and hexagonal boron nitride (hBN, Boren, Turkey) were used as starting materials. Experimental details were given in our previous study [15] but briefly explained here. A binder burnout process for Al₂O₃ powder was applied at 600°C for 30 minutes to remove binder from granulated powder. Al₂O₃ and glass granules were separately ball-milled in ethanol for 24 h. Then, a composition of 45 wt% Al₂O₃ and 55 wt% glass mixture (hereafter abbreviated as GSS5) was mixed with hBN at 1, 2.5, 5 and 10 wt% by ball milling for 24 h in ethanol with a ready-to-use vinyl-based binder solution (polyvinyl butyral and dibutyl phthalate as binder and plasticizer, methyl ethyl ketone and ethyl alcohol as the solvent) (TC-51, MZE Teknoloji Inc., Turkey). The Al₂O₃/glass/hBN composites will be hereinafter referred to as G55, G55-1, G55-2, G55-5, and G55-10, which corresponds to 0, 1, 2.5, 5 and 10 wt% hBN, respectively. The samples were pressed at 100 MPa using a uniaxial press. They were sintered at various temperatures in the range of 800–900°C for 1 h in air, with a heating rate of 5°C/min. Archimedes method was used to measure bulk density. The G55-5 and G55-10 samples were also processed by cold isostatic pressing method at 250 MPa and by tape casting. Powders were mixed with a ready-to-use vinyl-based binder solution at 50 wt% solid loading, using a high-speed mixer (FlackTek, DAC 150.1 FVZ) run at 3500 rpm for 5 min and then tape-casted on a silicon-coated Mylar film at a casting rate of 5 cm/sec with a blade gap of 250 μm. After drying at room temperature, green samples were cut into desired sizes. The green tapes were put on top of each other, kept at 80°C for 30 minutes and then laminated by applying 50 MPa for 10 minutes. Binder burnt-out was carried out at 600°C for 30 min with a slow heating rate of 1°C/min and then sintered in air at 800°C for 1 h with a 5°C/min heating and cooling rate. The phase identification was checked on the samples polished and annealed at 500°C for 30 min, by an X-ray diffractometer (Rigaku, MiniFlex600) with Cu/Kα radiation and a scan rate of 2°/min. Microstructure development and elements were examined by a Scanning Electron Microscopy equipped with an Energy Dispersive Spectroscopy (SEM-EDS, Hitachi SU1000). The thermal conductivity (k) was calculated by multiplying specific heat (cₚ), thermal diffusivity (a) and density. The specific heat was measured by a differential scanning calorimeter (DSC, Netzsch STA 449F3A) and the thermal diffusivity was determined by a laser flash apparatus (Netzsch LFA 457). The BET method was used to measure the specific surface area (Ququantachrome ASiQwin). The dielectric constant (K) and loss were measured by using an inductance–capacitance–resistance meter (Hioki IM3570).

3. Results and discussion

Spray-granulated Al₂O₃ powder after burnout and mm-sized glass flakes were first separately ball-milled for 24 h to decrease particle size. Al₂O₃ powder had a d₅₀ = 0.5 μm and SSA = 6.44 m²/g, glass powder had a d₅₀ = 2.13 μm and SSA = 1.89 m²/g. Its sintering, softening, sphere, half sphere and melting temperatures were 726°C, 852°C, 958°C, 1088°C and 1180°C, respectively. The glass composition comprised 65.8 wt% SiO₂, 15.1 wt% Al₂O₃, 11.7 wt% CaO, 4 wt% Na₂O and 3.4 wt% K₂O [15]. As-received plate-like hBN had an SSA = 18.23 m²/g and averaged mean thickness of 91 nm ±19 nm and mean diameter of 1.1 μm ±0.6 μm as determined from SEM.

Figure 1 shows densification and apparent porosity (AP) of the dry-pressed samples as a function of hBN content and temperature. The solid lines are drawn to guide the eye. In general, as the hBN content increased, bulk densities decreased at each sintering temperature due to lower density of hBN (e.g., the
theoretical density of Al₂O₃ = 3.93 g/cm³, glass = 2.43 g/cm³ and hBN = 2.1 g/cm³ [7], respectively. Correspondingly, the AP decreased with increasing densification. The G55-10 bulk densities were the lowest at all temperatures. The bulk densities and respective densification temperatures for each composite were decided based on the lowest AP and water absorption (WA) as calculated from the Archimedes method. Maximum densification was attained at 800°C for the G55 (2.89 g/cm³, AP = 0.13% and WA = 0%), G55-1 (2.81 g/cm³, AP = 0.17% and WA = 0.16%), G55-2.5 (2.75 g/cm³, AP = 0.23% and WA = 0.08%), and at 900°C for the G55-5 (2.48 g/cm³ and AP = 0.05% and WA = 0.02%) and for the G55-10 (2.28 g/cm³ AP = 14.87% and WA = 6.51%). The G55-5 and G55-10 samples had lower densities even after they were sintered at higher temperatures. Therefore, they were fabricated by other methods such as cold isostatic pressing (CIP) and tape casting to improve densification further at high hBN loadings. Figure 2 compares the densification and AP of the samples fabricated via different methods and sintered at 800°C. Bulk densities were 2.54 g/cm³ and 2.28 g/cm³ for the G55-5 and G55-10 samples prepared by CIP, respectively. The bulk density increased to 2.65 g/cm³ and the AP decreased to 0.7% with a WA of 0.26% for the G55-5 prepared by tape casting. In other words, the densification temperature was successfully decreased from 900°C to 800°C by changing the fabrication method from dry pressing to tape casting for the G55-5 samples. Note that the G55-10 was not successfully processed by tape casting due to the very high viscosity of the suspension caused by the shape and high surface area of the hBN phase. These results suggest that a homogenous particle packing in the green body was provided by tape casting (or colloidal processing) method due to dispersion of the plate-like hBN particles, which allowed high hBN loading into the dense Al₂O₃/glass structure. Similar effects of the platelet hBN particles on densification were reported in barium aluminosilicate (BaAl₂Si₂O₇, BAS)/hBN (10 to 50 wt%) composites fabricated by hot pressing at 1500°C [16]. The bulk density decreased from 3.18 g/cm³ at 10 wt% hBN without any visible micro-cracks to 2.22 g/cm³ at 50 wt% hBN with cracks and voids. Cho et al. [17] also reported limited densification in AlN (5–20 vol%)-hBN ceramics due to porosity formation induced by plate-like hBN shape.

Figure 3 illustrates XRD patterns of the dry-pressed composites sintered at 800°C. The polished samples were annealed at 500°C to relieve mechanical stress before the measurements. Al₂O₃ (Corundum, Card number: 00–010-0173) was the main crystalline phase for each composition. Anorthite (Ca₆Na₂)(Al₄Si₄O₁₂) (Card number: 00–014-1481) and hBN (Card number: 01–074-1977) phases are also marked on the patterns. Anorthite crystallization was only discernable but the main hBN peak intensity at 2θ = 26.6° increased from the G55-1 to G55-10, which indicates that hBN neither chemically reacted with the other phases nor decomposed with temperature. Chemical stability of hBN is extremely important at helping decrease dielectric constant and increase the thermal conductivity of the composites. Figure 4 compares phase evolution as a function of temperature for the G55-5 samples fabricated by dry pressing and tape casting. The most distinguishing feature between them was the orientation of the hBN particles (i.e., basal plane (0002)) during tape casting, which also considerably contributed densification at 800°C (see Figure 2) by inhibiting porosity resulted from mainly hBN agglomeration. Anorthite phase formed and its amount considerably increased with increasing temperature for the tape-cast samples. The intensities of the anorthite peak at 2θ = 25.9° and Al₂O₃ peak at 2θ = 25.5° (i.e., Iₐnor/Ip₂O₃) were used to qualitatively calculate anorthite ratio with temperature. Note that the main Al₂O₃ peak at 2θ = 35.1° was not used due to a background hump (see the Glass XRD pattern in Figure 3). The intensity ratio is about 0.04 for both dry-pressed and tape-cast samples sintered at 800°C (i.e., almost no anorthite formation based on XRD detection limit), 0.73 for the Tape-850°C and 1.29 for the Tape-900°C samples. The densification levels also changed with temperature, that is,
Figure 3. XRD patterns of the dry-pressed samples sintered at 800°C.

Figure 4. XRD patterns of the dry-pressed and tape-casted G55-5 samples sintered at various temperatures.

2.65 g/cm³ (AP = 0.7%) at 800°C, 2.63 g/cm³ (AP = 0.95%) at 850°C, and 2.49 g/cm³ (AP = 8.71%) at 900°C. These results indicate that sintering temperature is important to control both densification and phase evolution, which is critical for dielectric and thermal properties.

Figure 5 shows SEM pictures of the samples sintered at 800°C. Al₂O₃ particles were uniformly dispersed in the G55 sample without any visible pores. The dry-pressed G55-2.5 and G55-5 samples had visible pores in regions where the hBN particles were mainly agglomerated or randomly oriented, as shown by the arrows in Figure 5b and 5c. However, the tape-casted G55-5 sample had mostly dispersed and aligned platelet hBN particles (See also XRD pattern in Figure 4) as shown by the arrows in Figure 5d, which inhibited pore formation and correspondingly enhanced densification, as supported by Figure 2. Because the LTCC process requires tape casting to fabricate thin dielectric layers, dense G55-5 sample preparation by tape casting is critical for reliable property characterizations at high hBN loadings.

The dielectric properties of a material are dependent mainly on several factors such as glass content, porosity (or densification) and crystalline phases present. Figure 6 shows the hBN dependence of the dielectric constant (K) and loss measured at 5 MHz for the samples sintered at 800°C. The dashed lines are drawn to guide the eye. The G55, G55-1 and G55-2.5 specimens were produced by dry pressing, and the G55-5 sample was produced by tape casting. Note that K (loss) = 10.19 (0.0018) and K (loss) = 6.37 (0.0016) at 5 MHz for Al₂O₃ and glass end compositions, respectively. In general, K decreased with increasing hBN content and it was almost leveled off after 2.5 wt% hBN. In other words, the K values at 5 MHz were 7.3 for the G55, 7.2 for the G55-1, 6.6 for the G55-2.5 and 6.55 for the G55-5. Because all samples had almost zero AP (i.e., less than 0.7%) and WA (i.e., less than 0.3%), the decrements (or, alternatively, enhancement) in K were mainly attributed to the lower K of hBN (K = 4–4.4 at 1 MHz [7,10], K = 4.5 and loss = 0.0003 at 1–10 GHz [11]). Note that the G55-10 sample prepared by dry pressing had a much lower K = 5.17 at 5 MHz due to very high porosity (AP = 19.8%). Figure 6 also compares the effect of sintering temperature on K for the tape-casted G55-5
Figure 5. SEM pictures of the samples sintered at 800°C; (a) G55, (b) G55-2.5 hBN, (c) dry-pressed G55-5 hBN and (d) tape-casted G55-5 hBN.

Figure 6. Dielectric properties measured at 5 MHz for the samples sintered at 800°C.

samples. K slightly increased from 6.55 to 6.76 when the sintering temperature was increased from 800°C to 850°C although both samples had similar density and AP, which can be attributed to more anorthite crystallization (e.g., intensity ratio increased from 0.04 to 0.73). The K (loss) values at 1 MHz for single crystal and amorphous anorthite are 7.14 (0.0011) and 7.5 (0.0024), respectively [18]. Therefore, anorthite crystallization gave rise to higher K. However, the sample sintered at 900°C had a lower K = 6.24 due to its higher AP = 8.71%, despite its much higher anorthite crystallization (e.g., intensity ratio of 1.29). Therefore, porosity (K = 1 [19]) tends to decrease and anorthite tends to increase overall K of the composites. Porosity was reported to decrease K for Al2O3, SiO2, Si3N4 and BN ceramics [11]. Similar hBN and porosity effects were also observed in other systems such as hBN/Si3N4 composites [14,20]. Particularly, full densification (or near zero AP) without in-situ anorthite crystallization is very critical at reducing K because signal propagation delay is one of the most important parameters directly associated with it in the LTCC electronic packaging:

\[
t_d = \frac{l}{\sqrt{\varepsilon c}}
\]

where \(t_d\) is propagation delay (sec), \(l\) (m) is the metal line length and \(c\) is the speed of light (m/sec). It is obvious that a reduction in K is strongly required for high-speed signal transmission [21,22]. Figure 6 also shows that dielectric loss was almost constant up to 2.5 wt% hBN (e.g., 0.0057–0.0063) and then increased to 0.013 at 5 wt% hBN for the samples sintered at 800°C. Dielectric loss was relatively higher for the G55-5 samples sintered at 850°C (e.g., 0.031) and 900°C (e.g., 0.024), which may be attributed to the porosity and/or composition. Because each component (e.g., Al2O3, hBN and in-situ crystallized anorthite, and glass) has a loss value between 0.0003 and 0.0024, porosity may be responsible for increasing the loss. Porosity definitely decreases K due to K = 1 for air [19] but has various results on the loss behavior such that it increased the loss for BN and Si3N4 while increased it for Al2O3 and SiO2 ceramics [11]. Because the composites had dominantly Al2O3 and SiO2 in the compositions, they possibly controlled the overall loss with increasing porosity (e.g., AP = 0.13% for the G55, AP = 0.17% for the G55-1, AP = 0.23% for the G55-2.5 and AP = 0.7% for the G55-5 at 800°C). Porosity was reported to decrease loss in the hBN/Si3N4 composites as well [20].

A high thermal conductivity (k) is strongly desired at the LTCC applications for a more efficient and reliable packaging to dissipate heat generated during service. Heat removal has become even more critical with increasing needs to produce high density and high
power devices operating at high speeds [21,23]. Figure 7 compares k of the samples sintered at 800°C. The G55, G55-1, G55-2.5 and G55-10 samples were produced by dry pressing and the G55-5 sample was produced by tape casting. In general, the temperature dependence between 75°C and 250°C almost remained constant for each set. A high k of hBN [7,8] considerably improved the overall k of the composites. Note that the end compositions Al₂O₃ and glass have k = 36 W/m·K [24] and k = 0.85 W/m·K [25] at 25°C, respectively. The mean k values between 75°C and 250°C are 1.86 W/m·K for the G55, 2.09 W/m·K for the G55-1, 2.17 W/m·K for the G55-2.5 and 2.43 W/m·K for the G55-5. Similar trend was also observed in the hBN/BAS system such that k increased from 2.5 W/m·K (10 wt% hBN) to 7.2 W/m·K (50 wt% hBN) at 100°C [13]. k decreased to 2.24 W/m·K for the G55-10 due to the porosity effect (i.e., higher AP or low densification). A mean k of 1.37 W/m·K between 75°C and 250°C was measured for the composite without hBN (i.e., the G55) sintered at 850°C [15] due possibly to anorthite crystallization (intensity ratio of 0.83) because the intensity ratio was 0.04 for the sample sintered at 800°C. In actual fact, the G55-5 composite must have reached to a higher k because aligned platelet hBN particles had a lower k perpendicular to the basal plane (or along the c axis or the k measurement direction) [7,9]. Note that the dry-pressed composites had averaged (or isotropic) k values due to random orientation of the hBN particles, as compared to the anisotropic k values due to the aligned particles during tape casting (see Figures 4 and 5). Therefore, a higher k is expected parallel to the basal plane (or, alternatively, a faster heat dissipation toward the edges of the LTCC modules). Similar anisotropic thermal and mechanical properties were also reported in the hot-pressed Al₂O₃/hBN composites [26]. It was determined in our earlier study [15] that silver electrode was applied on the tape-cast layers and successfully co-fired at 850°C, stating that dense ceramics were fabricated without any additional phase, microcracking or shape distortion. The dielectric and thermal properties reveal that hBN addition enhanced k and k up to 5 wt% hBN provided that the AP was near zero. Furthermore, it is definitely worth investigating the (anisotropic) properties based on densification and distribution of phases (e.g., amorphous and crystalline anorthite, possible dissolution of Al₂O₃ in glass, change in glass composition/network with temperature, hBN agglomerating and/or alignment, etc.) in order to fully understand the processing–property relationship.

Ceramic fabrication method and sintering temperature are important parameters to control densification (e.g., porosity effect) and phase formation (e.g., anorthite phase effect), which ultimately affects final dielectric and thermal properties. Some commercial LTCC dielectric and thermal properties are as follows: Kyocera [27] (GL330: k = 7.8 at 1 MHz, k = 4.3 W/m·K and GL771: k = 5.3 at 1 MHz, k = 2 W/m·K); Micro Systems Engineering [28] (951AT: sinterable at 900°C, k = 7.8 at 3 GHz, k = 2.8 W/m·K and 943A5: k = 7.4 at 3 GHz, k = 4.9 W/m·K); Heraeus [29] (X200: sinterable at 880°C, k = 8.8–9.5 at 30 MHz, k = 3 W/m·K); Ferro [30] (L8: sinterable at 850°C, k = 7.2 ± 0.2 at 10 GHz, k = 2 W/m·K and A6M/A6M-E: sinterable at 850°C, k = 5.7 ± 0.2 at 10 GHz, k = 2 W/m·K). In general, high k comes with high K such as K = 8.06 at 7 GHz and k = 3.1 W/m·K in the CaO-B₂O₃-SiO₂ glass/Al₂O₃ composite [3], and k = 7.2 W/m·K and K = 11.3 at 1 MHz for BiO₂-ZnO-B₂O₃-SiO₂ glass/40 wt% Al₂O₃ composite with a secondary ZnAl₂O₄ phase after sintered at 900°C [31]. The G55-5 sample has comparable dielectric and thermal properties to the commercial products with a densification temperature of 800°C, k = 6.55 at 5 MHz and k = 2.43 W/m·K between 75°C and 250°C. Therefore, hBN phase effectively optimizes the dielectric and thermal properties and makes the G55 composition a potential candidate for the LTCC applications.

4. Conclusions

Al₂O₃/glass/hBN composites were successfully fabricated for the LTCC applications. Maximum densification was attained at 800°C for the 0–2.5 wt% hBN composites and at 900°C for the 5–10 wt% hBN composites. The 5 wt% hBN composite was densified at 800°C when the fabrication method was changed to tape casting due to alignment and homogeneous distribution of the hBN particles within the Al₂O₃/glass structure. XRD results proved that hBN neither chemically reacted with the other phases nor decomposed with temperature, which was critical to increase thermal conductivity to decrease dielectric constant at the same time. Dielectric constant of the dense composites decreased (or, alternatively, enhanced) with increasing hBN content such that...
the dielectric constant at 5 MHz was 7.3 for the 0 wt% hBN and 6.55 for the 5 wt% hBN composites. Anorthite crystallization started at 850°C and slightly increased the dielectric constant to 6.76. Therefore, full densification without in-situ anorthite crystallization was very important at reducing dielectric constant to lower signal propagation delay. In addition, hBN addition strongly improved mean thermal conductivity from 1.86 W/m-K for the 0 wt% hBN to 2.43 W/m-K for the 5 wt% hBN between 75°C and 250°C. The 5 wt% hBN composite had comparable dielectric and thermal properties to the commercial products with a densification temperature of 800°C (density of 2.65 g/cm³, apparent porosity of 0.7% and water absorption of 0.26%). Therefore, the hBN phase itself effectively optimized both dielectric and thermal properties at the same time and made the Al₂O₃/glass/hBN composites a promising candidate for the LTCC applications.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Disclosure statement

There are no relevant financial or non-financial competing interests to report.

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