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Introduction

Fluorophlogopite mica-based glass-ceramics are technologically important materials because of their well-grained microstructure, resulting in a wide range of thermal expansion value suitable for high temperature sealing applications.^{1–3} K₂O– MgO–B₂O₃–Al₂O₃–SiO₂–F is a type of magnesium-boro-aluminosilicate (MBAS) system that can be easily crystallized into mica glass-ceramics containing fluorophlogopite [KMg₃(AlSi₃O₁₀)F₂] phase.^{3,4} For this, the most studied technique is the controlled *in situ* crystallization of glass over a temperature 800 °C.⁴ In addition to the flexibility to develop an improved fine-grained microstructure with desired thermal properties, these glassceramics exhibit consistent reproducibility of properties due to the homogeneity of the as-cast melt glass.^{4–6} They typically contain a finite quantity of crystalline ceramic phase produced by the controlled nucleation of highly viscous glass forming melts.⁵

Mica glass-ceramics with dense nanocrystalline-grained microstructure and improved thermal properties are interesting materials for high temperature sealing applications such as solid oxide fuel cells (SOFCs).⁷ This is typically due to their

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Nanocrystalline microstructure in Sm^{3+} and Gd^{3+} doped K₂O-MgO-Al₂O₃-SiO₂-F glass-ceramic sealant (SOFC)

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In order to demonstrate the effects of Sm³⁺ and Gd³⁺ ions on the crystalline microstructures of the magnesium-boro-alumino-silicate (MBAS) system, the K₂O-MgO-B₂O₃-Al₂O₃-SiO₂-F glass doped with 0–5 mol% Sm₂O₃ and Gd₂O₃ were synthesized by melt-quenching (1550 °C). The addition of Sm³⁺ and Gd³⁺ content was found to increase the density (2.74–2.91 g cm⁻³) of the base glass. By controlled heat-treatment at 950 °C, the MBAS glasses were converted into opaque glass-ceramics with crystalline phases (XRD), containing fluorophlogopite mica [KMg₃(AlSi₃O₁₀)F₂], norbergite [Mg₂SiO₄·MgF₂] and enstatite [MgSiO₃]. The FESEM study revealed the development of rock-like and plate-like crystallite particles (average size 2–4 µm) randomly dispersed in the heat-treated MBAS microstructure, which on the addition of Sm³⁺ and Gd³⁺ ions is restructured into nanocrystalline (size = ~50–400 nm) morphology. The substantial change in the microstructure influenced the corresponding density and thermal expansion properties. The coefficient of thermal expansion for MBAS was estimated to be 10.47(±0.10) × 10⁻⁶ K⁻¹ (50–800 °C), which increased to 11.11–11.29 × 10⁻⁶ K⁻¹ when doped with Sm³⁺ and Gd³⁺. Such large thermal expansion makes the Sm₂O₃- and Gd₂O₃- doped K₂O-MgO-B₂O₃-Al₂O₃-Al₂O₃-SiO₂-F glasses suitable for high temperature sealing applications (like SOFC).

compatible thermal expansion with other components used (viz. metal electrode, solid electrolyte, interconnect material, etc.) in SOFC cell.^{6,7} Moreover, they possess layered crystalline structure that can avert the generation and growth of micro-crack during thermal recycling operation performed at high temperature.⁶⁻⁸ However, the large thermal shock resistivity for those mica glassceramics arises due to the wide thermal expansion value.9-11 Moreover, the wide thermal expansion in the K₂O-MgO-B₂O₃-Al₂O₃-SiO₂-F glasses is obtained due to the layered structure of the mica crystals, which permit structural relaxation along the planes of the flat structural network.^{5,10} In general, the thermal properties of the mica glass-ceramic body are affected by the particle size, amount of precipitated mica crystals and their strength.¹² In the production of glass-ceramics, two major factors, namely (i) nucleating agents, and (ii) temperature and time of the heattreatment influence the size and number of the crystals.^{4,5} In magnesium-boro-alumino-silicate based glass-ceramic, the tuning of crystallization has been studied with the doping of nucleating agent such as rare-earth (RE) ions having high ionic field strength.9,10 Compared to the mono- and di-valent modifier ions, the trivalent RE ions (viz., Nd^{3+} , Sm^{3+} , and Gd^{3+}) play different structural roles both over short and intermediaterange in the alumino-silicate glass.9-11 During the process of crystallization the RE ions (RE³⁺) tend to 'cluster' that makes a minority of oxygen ions (O²⁻) involved in the RE-O-RE linkages, and isolated from the aluminosilicate glass.^{10,13} Nicoleau et al.¹³

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Paper

studied the impact of rare-earth silicate crystallization on the borosilicate glass structural configuration and argued that the crystallization leads to the reorganization of the cation distribution around the rare-earth elements. Due to low solubility, the lanthanides lead to crystalline phases in the Si–O–B based glass during cooling.^{13,14} This means that the RE ions influence the crystallization behavior, which is essential for preparing glass-ceramics with desired thermal properties required for high-temperature sealing applications (SOFC).^{10–13} Salinigopal *et al.*¹⁴ studied the effects of Nd₂O₃ and Gd₂O₃ on the BaO–Al₂O₃–BiO₂–SiO₂ glass and observed that the coefficient of thermal expansion for glass-ceramics lie within the range 12.32–12.81 × 10⁻⁶ °C⁻¹, which is suitable for the solid oxide fuel cell (SOFC) applications.

In this study, based on the previous experiences, $^{9-11}$ 40SiO₂–12MgO–16Al₂O₃–10B₂O₃–10K₂O–12MgF₂ (mol%) glass doped with Sm₂O₃/Gd₂O₃ (5 mol%) was considered as the starting composition in order to achieve a fluorophlogopite (phase) dominated glass-ceramics possessing a high thermal expansion value (>11 × 10⁻⁶ K⁻¹ at 50–800 °C) suitable for high temperature sealant applications. In this regard, the role of Sm₂O₃ or Gd₂O₃ to improve the glass-ceramic morphology and thermal expansion was also investigated.

Experimental

Three different glasses of (i) base composition (mol%) 40SiO₂-12MgO-16Al₂O₃-10B₂O₃-10K₂O-12MgF₂ (G-1) and doped (5 mol%) with (ii) Sm₂O₃ (G-2) and (iii) Gd₂O₃ (G-3) were synthesized via a conventional melt-quench technique using highly pure reagent grade fine chemicals. Most of the chemicals used were in the form of oxides, hydroxides and carbonates as precursor materials: SiO₂ (Quartz Powder, LobaChemie, Mumbai, India), Mg(OH)₂ (97%, LobaChemie, Mumbai, India), Al(OH)₃ (97%, LobaChemie, Mumbai, India), H₃BO₃ (99.5%, LobaChemie, Mumbai, India), K₂CO₃ (98%, LobaChemie, Mumbai, India), MgF₂ (99.9%, Loba-Chemie, Mumbai, India), Sm₂O₃ (99.99%, Indian Rare Earths Ltd, Udyogamandal, India) and Gd₂O₃ (99.99%, Indian Rare Earths Ltd, Udyogamandal, India). Homogeneously mixed batches were allowed to melt at \sim 1550 °C (2 h) using an electric furnace (Kanthal), followed by stirring for 0.5 min with a silica glass rod in an open platinum (Pt) crucible. Molten glasses were then allowed to cast into a pre-heated carbon plate in open-air atmosphere. The as-synthesized glasses were then heat-treated at ~950 °C (2 h) for controlled crystallization.

The density (*d*) of the investigated glass and glass-ceramic bulk samples was determined (with an accuracy of $\pm 0.7\%$) by the Archimedes principle using distilled water as the immersion liquid (density = 1 g cc⁻¹) in a digital balance (MettlerToledo), which enables weighing the bulk solid in air (W_{air}) as well as in the solvent (W_{water}):

$$d = [W_{air}/(W_{air} - W_{water})]d_{water}$$

The crystallinity of the studied samples (glass and corresponding glass-ceramics) was checked *via* powder X-ray diffraction (XRD). All the patterns were recorded on a XPERTPRO MPD

diffractometer (PANalytical, Netherlands) operating with Ni-filtered Cu K α (λ = 1.5406 Å) radiation, irradiated at 40 kV and 40 mA. The crystalline phases were analyzed in the 2 θ range of 5–70° with a step size of 0.05° at room temperature.

The microstructural morphology of the studied glassceramics (heat-treated at 950 $^{\circ}$ C/2 h) were examined *via* field emission scanning electron microscopy (FESEM model S430i, LEO, CEA, USA) using polished glass-ceramic samples (chemically etched by immersion in 5 vol% aqueous HF solution for 5 min).

In order to investigate the thermal properties, the coefficient of thermal expansion (CTE) of the studied glass-ceramics were evaluated using a cylinder-shaped sample with a length of ~25 mm and diameter of ~6 mm using a horizontal dilatometer, NETZSCH DIL 402 PC (NETZSCH-Gerätebau GmbH, Germany) at a heating rate of 5 °C min⁻¹ under ±1% accuracy after calibration with a standard Al₂O₃ cylinder.

Results and discussion

The melt-quenched monoliths of $40\text{SiO}_2-12\text{MgO}-16\text{Al}_2\text{O}_3-10\text{B}_2\text{O}_3-10\text{K}_2\text{O}-12\text{MgF}_2-\text{Sm}_2\text{O}_3/\text{Gd}_2\text{O}_3$ (0–5 mol%) composition were opaque in nature. Base glass G-1 contained no rare-earth composition; it possessed density value 2.74 ± 0.02 g cm⁻³. On adding Sm_2O_3 and Gd_2O_3 in the G-1 glass, the density increased to 2.85 ± 0.02 and 2.91 ± 0.02 g cm⁻³, respectively.¹⁰ The as-synthesized glasses were heat-treated at 950 °C for 2 h over, which they were converted into the glass-ceramics. The crystal-line nature of the glasses and corresponding glass-ceramics were accounted from the XRD pattern taken in 5–70° (2θ). It is evident from Fig. 1 that the broad hump appearing at (2θ) 15–35° for all the glasses signifies their amorphous nature.^{10,12} On heating over 950 °C, those glasses converted into glass-ceramic signifying their crystalline pattern (XRD), as exhibited



Fig. 1 XRD pattern of the as-synthesized glasses (a) G-1 (b) G-2 and (c) G-3 showing the appearance of a broad hump in the range at (2θ) 15–35° signifying their amorphous characteristics (inset shows the density values of glasses).

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Fig. 2 XRD pattern of the heat-treated glass-ceramics (a) G-1 (b) G-2 and (c) G-3 showing their multi-crystalline nature with crystalline phases fluorophlogopite mica [KMg₃(AlSi₃O₁₀)F₂], norbergite [Mg₂SiO₄·MgF₂] and enstatite [MgSiO₃].

in Fig. 2. The crystalline peaks shown in Fig. 2 at the (2θ) positions of 8.92, 23.82, 26.92, 33.43, 34.18, 37.03, 44.54, 46.05, 50.42, 52.79, 56.48, 60.57 and 65.26°, corresponding to the (001), (112), (003), (200), (201), (132), (005), (222), (224), (115), (225), (331) and (007) planes are developed due to the formation of the phase fluorophlogopite mica, KMg₃AlSi₃O₁₀F₂ (molecular weight = 421, monoclinic end-centered system, JCPDS-PDF number 10-0494 & 71-1542; lattice parameter a = 5.299, b = 9.188, c = 10.13).^{3,5} All the peaks with corresponding planes are summarized in Table 1.

The characteristic peaks appearing at (2θ) 19.93, 22.67, 32.42, 39.90, 41.75, 45.40 and 48.94° diffracted from the (021), (111), (131), (210), (004), (142) and (151) crystalline planes, correspond to the formation of magnesium fluoride silicate, 'Norbergite' (Mg₂SiO₄·MgF₂), molecular weight = 203, JCPDS file number 71-2401 (orthorhombic, primitive system; lattice parameter *a* = 4.710, *b* = 10.27, *c* = 8.747). Norbergite is formed in all the glass-ceramics; however, the development of fluorophlogopite mica is supported by rare-earth ions.^{10,13,14} A different crystalline phase enriched by the Mg and Si contents, magnesium silicate, 'enstatite' (MgSiO₃), molecular weight = 100.39, was also found to appear with peaks (2 θ) 30.20, 36.78 and 60.45° due to the crystalline planes (321), (112) and (650); JCPDS file number 83-2057 (orthorhombic, primitive system; lattice parameter

a = 18.21, b = 8.813, c = 5.179.¹⁵ During the heat-treatment, Mg^{2+} and F^- ions tend to form MgF_2 precipitates at ~600-650 °C.¹⁶ The tiny particles of MgF₂ then mix with magnesium silicates to form the additive compound *i.e.*, norbergite crvstallites.^{10,16} In the base glass-ceramic, the XRD pattern manifests the appearance of norbergite and enstatite phases predominantly. The trivalent ions Sm³⁺ or Gd³⁺ strongly support the heterogeneous phase separation in the SiO₂-MgO-Al₂O₃- B_2O_3 - K_2O - MgF_2 composition.^{10,14} Due to the large ionic field strength (charge/radius) and small critical nuclei, they tend to form 'clusters' during initial heating, and hence are isolated from the silicate glass network (Si-O-Si).^{10,11} Thus, the maximum XRD peaks corresponding to the fluorophlogopite phase are observed in the case of G-2 (i.e., Sm2O3 content) and G-3 (*i.e.*, Gd₂O₃ content) glass-ceramics.^{13,14} Under the same heattreatment, the slight shift of the diffraction peaks in G-2 and G-3 (Fig. 2) is associated with the crystallite size and high concentration of the fluorophlogopite phase.^{15,17}

Mica belongs to the monoclinic system with the co-existence of several types of atoms, where the volume fraction, crystallinity and grain size of the crystalline phase is controlled by the heat-treatment as well as the doping agents.^{5,17} In the present report, the controlled nucleation in the SiO₂-MgO-Al₂O₃-B₂O₃-K₂O-MgF₂ glass is performed under two selected parameters: (i) heat-treatment at 950 °C for 2 h and (ii) the addition of 5 mol% Sm₂O₃ and Gd₂O₃. Thus, it is of interest to compare the microstructures of the crystallized glasses of same composition with different RE ions. Volume crystallization with a rather fine morphology was observed for all the glass-ceramics studied under same heat-treatment.¹⁸⁻²⁰ The examples of the FESEM micrographs (taken using etched G-1 to G-3 specimens) are given in Fig. 3. The XRD analysis of these samples indicated that the base glass-ceramic microstructure predominantly contained norbergite and enstatite constituents, and the rare-earth doped samples (Sm₂O₃ and Gd₂O₃) largely comprised fluorophlogopite mica particles.¹⁰ As seen from Fig. 3a, the G-1 glass-ceramic microstructure is composed of rock-like and plate-like crystallite particles (average size 2 to 4 µm), which are randomly dispersed throughout the matrix. In a closer look it seems that the plenty of rock-shaped (100-500 nm sized) particles are in-homogeneously positioned to fill the gaps amongst the plate-shape crystallites of dimension 1-4 µm. The bulk density of the G-1 glass-ceramic was calculated as $2.77 \pm 0.02 \text{ g cm}^{-3}$. In the presence of Sm_2O_3 (*i.e.*, Sm^{3+}), the glass-ceramic structure is largely changed into the nanocrystalline morphology,¹⁰⁻¹⁴ where 50-200 nm sized spherical droplets such as crystallite particles are homogeneously distributed to

Table 1 XRD peaks and corresponding planes of different crystalline phases developed in studied $K_2O-MgO-B_2O_3-Al_2O_3-SiO_2-F$ glass-ceramics heat-treated at 950 °C for 2 h

| Peak position (2θ) (degree) | Corresponding planes | Crystalline phase | JCPDS file |
|---|--|--|-------------|
| 8.92, 23.82, 26.92, 33.43, 34.18, 37.03, 44.54, | (001), (112), (003), (200), (201), (132), (005), | Fluorophlogopite mica | 10-0494 and |
| 46.05, 50.42, 52.79, 56.48, 60.57, 65.26 | (222), (224), (115), (225), (331), (007) | [KMg ₃ AlSi ₃ O ₁₀ F ₂] | 71-1542 |
| 19.93, 22.67, 32.42, 39.90, 41.75, 45.40, 48.94 | (021), (111), (131), (210), (004), (142), (151) | Norbergite (Mg ₂ SiO ₄ ·MgF ₂) | 71-2401 |
| 30.20, 36.78, 60.45 | (321), (112), (650) | Enstatite (MgSiO ₃) | 83-2057 |



Fig. 3 FESEM photomicrograph of G-1 (a), G-2 (b) and G-3 (c) glass-ceramics heat-treated at 950 °C, showing the restructure of plate-like crystallites into spherical granule-like crystallites in attendance of with the RE content (Sm₂O₃ and Gd₂O₃).

form a fine-grained microstructure (Fig. 3b). Such a compact morphology is ascribed for its high density value (3.02 \pm 0.02 g cm⁻³).^{6,20} During the heat-treatment at 950 °C, the nucleating agents such as Sm³⁺ or Gd³⁺ ions can either support the heterogeneous phase separation or these can cause the accumulation in a specific microphase or nanophase of the phase separated glass.^{3,10} Those trivalent ions Sm³⁺ or Gd³⁺ having large ionic field strength (charge/radius) and smaller critical nuclei tend to form 'cluster', which makes a minority of oxide ions involved in the Sm-O-Sm or Gd-O-Gd linkages, and hence isolated from the silicate glass network (Si-O-Si).^{10,11,13} When Gd_2O_3 (*i.e.*, Gd^{3+}) is present in the base composition G-1, the spherical granules are agglomerated in the surrounds of Gd³⁺ to form 'cluster'. The clusters then shaped into bigger spherical crystals mostly of size, 200–400 nm (Fig. 3c).^{10,14} From samarium (Sm) to gadolinium (Gd) the ionic radii decreases and hence the ionic field strength increases by virtue of "lanthanide contraction". Therefore, it can be guessed that Gd³⁺ have occupied the interstitial places in the glass network governed by Si-O-Si/B-O-B/Si-O-B and their increase in field strength as well as atomic weight have made the glass-ceramic network more compact, resulting in an increase in the molecular weight without increasing the volume.¹⁰ Thus, the maximum density is estimated for G-3 as 3.06 \pm 0.02 g cm $^{-3}.^{6,20}$

The dilatometry of the heat-treated samples (i.e., glassceramics) was carried out in order to investigate the thermal expansion-sealant (SOFC) behavior.^{21,22} A plot of the CTE of the glass-ceramics between 400 °C and 800 °C is presented in Fig. 4. Linear increase in CTE up to 800 °C was obtained for all the studied glass-ceramics; however, the linear trend is quite different for the Sm2O3- and Gd2O3-doped samples. For the G-1 glass-ceramic, the CTE at 50–500 $^{\circ}$ C was 8.00(\pm 0.08) \times $10^{-6}~\text{K}^{-1}$ and increased to 8.20, 9.37 and 10.54 $\times~10^{-6}~\text{K}^{-1}$ at 50-600, 50-700 and 50-800 °C, respectively. For G-2, where 5 mol% Sm₂O₃ was added, the CTE was evaluated as $8.44(\pm 0.08)$ and 8.56(± 0.09) \times 10⁻⁶ K⁻¹ at 50–500 °C and 50–600 °C, respectively. The obtained CTE values are summarized in Table 2. For fluorophlogopite mica-based glass-ceramics, the CTE strongly depends on the size, shape of crystallite particles as well as crystalline fraction in the microstructure.^{23,24} The dopant ions Sm³⁺ or Gd³⁺ have tendency to participate in the overall bonding of the MBAS glass to tailor the thermal expansion since their structural roles in the Si-O-Si matrix are related to their size and coordination number.9-11 Nanocrystalline morphology advocates structural relaxation in the G-2 glass-ceramic in comparison



Fig. 4 Variation of thermal expansion as a function of temperature for fluorophlogopite glass-ceramics (heat-treated at 950 °C) with and without doped rare-earth ion content (inset shows the density of glass-ceramics and their CTE value at the SOFC operation temperature).

Table 2 Variation of the thermal expansion value (CTE) of different $K_2O-MgO-B_2O_3-Al_2O_3-SiO_2-F$ glass-ceramics heat-treated at 950 °C for 2 h

| Sample identity | Coefficient of thermal expansion (× 10^{-6} K^{-1}) | | | | |
|--------------------|--|--|--|---|--|
| | 50–500 °C | 50–600 $^{\circ}\mathrm{C}$ | 50–700 °C | 50-800 °C | |
| G-1 G-2 G-3 | $8.00(\pm 0.08)$ $8.44(\pm 0.08)$ $8.56(\pm 0.09)$ | $8.20(\pm 0.08)$ $8.56(\pm 0.09)$ $8.53(\pm 0.09)$ | $\begin{array}{c} 9.37(\pm 0.09) \\ 10.22(\pm 0.10) \\ 9.89(\pm 0.10) \end{array}$ | $\begin{array}{c} 10.47 (\pm 0.10) \\ 11.11 (\pm 0.11) \\ 11.29 (\pm 0.11) \end{array}$ | |

to the G-1 system.^{10,13,23} At 50–700 and 50–800 °C, large CTE values were thus estimated for the G-2 sample with the values being 10.22(±0.10) and 11.11(±0.11) × 10⁻⁶ K⁻¹, respectively. Gd³⁺ having a smaller size gets surrounded by the [AlO₄]⁻ tetrahedra during heat-treatment. In the present composition, 5 mol% Gd₂O₃ was present in the 40SiO₂–12MgO–16Al₂O₃–10B₂O₃–10K₂O–12MgF₂ system and the microstructure of that became less homogeneous.^{10,11} As is evident from Fig. 3c, the dimension of the spherical crystallite particles increased, whereas the compactness of the morphology decreased. Because of the combining effects, the CTE value of G-3 is comparatively larger at 50–800 °C (Table 2).^{9,10}

For intermediate temperature (700–800 $^{\circ}$ C) solid oxide fuel cell (SOFC) designs, the glass sealant must have thermal expansion

characteristics that do not contribute to the creation of thermal stress between a variety of ceramic and metallic materials used in the SOFC stack; must be thermochemically compatible with the other materials; must be stable at operational temperatures (700–800 °C) of SOFCs. These all requirements are however controlled by the CTE value.^{25–29} Thus, a linear thermal expansion up to 800 °C as well as large CTE value at that temperature are prime requisites for SOFC sealant.²⁸ The large CTE (>11 × 10^{-6} K⁻¹) at 50–800 °C as observed for the samples G-2 and G-3 (Table 2), is well-matched with the SOFC components like electrode (Ni/Fe), solid electrolyte (YSZ), interconnect (Crofer-22APU) *etc.* in the operating temperature ~700–800 °C.^{23,24} Hence, Sm₂O₃ and Gd₂O₃ doped SiO₂–MgO–Al₂O₃–B₂O₃–K₂O–MgF₂ glasses can act as a potential SOFC sealant material.^{13,30}

Conclusions

This report highlights the effect of the addition of samarium (Sm³⁺) and gadolinium (Gd³⁺) on the nucleation behavior, alteration of microstructure, physical and thermal properties of low alkali containing magnesium-boro-alumino-silicate (MBAS) glass. 0–5 mol% Sm₂O₃ and Gd₂O₃ doped K₂O–MgO–B₂O₃–Al₂O₃–SiO₂–F glasses were synthesized by melt-quenching at 1550 °C. The major conclusions are summarized below:

• Base glass G-1 (no rare-earth composition) possessed density value of 2.74 ± 0.02 g cm⁻³, which after the addition of Sm³⁺ and Gd³⁺ increased to 2.85–2.91 g cm⁻³.

• The MBAS glasses, by controlled heat-treatment at 950 $^{\circ}$ C (2 h), were converted into multi-crystalline grass-ceramics with predominantly crystalline phase (XRD) containing fluoro-phlogopite mica [KMg₃(AlSi₃O₁₀)F₂], norbergite [Mg₂SiO₄· MgF₂] and enstatite [MgSiO₃].

• Field emission scanning electron microscopy revealed the development of rock-like and plate-like crystallites (average size $\sim 2-4 \ \mu$ m) randomly dispersed in the base glass-ceramic matrix. In the presence of Sm³⁺ and Gd³⁺, the microstructure restructured into nanocrystalline morphology packed by droplet-like crystallite particles (size $\sim 50-400 \ nm$).

• The significant variation in microstructure is ascribed to the corresponding density and thermal expansion value. The coefficient of thermal expansion (CTE) for the base glass-ceramic was estimated to be $10.47(\pm 0.10) \times 10^{-6} \text{ K}^{-1}$ at 50–800 °C that increased to $11.11-11.29 \times 10^{-6} \text{ K}^{-1}$ at 50–800 °C for glass-ceramics containing Sm³⁺ and Gd³⁺. Such large thermal expansion makes the Sm₂O₃-and Gd₂O₃-doped K₂O-MgO-B₂O₃-Al₂O₃-SiO₂-F glasses applicable for high temperature sealing application (like SOFC).

Conflicts of interest

There are no conflicts to declare.

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