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# Densification, microstructural evolution, and dielectric properties of hexagonal $Ba(Ti_{1-x}Mn_x)O_3$ ceramics sintered with fluxes

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ABSTRACT

Recently, doped hexagonal $BaTiO_3$ (6h-$BaTiO_3$) ceramics have been reported as potential candidates used in microwave dielectric resonators. However, similar to other common microwave ceramics, doped 6h-$BaTiO_3$ ceramics require a high sintering temperature, greater than 1300 °C. In this study, the effect of sintering aids, including $Bi_2O_3$, $B_2O_3$, $BaSiO_3$, $Li_2CO_3$, CuO, $V_2O_5$, $5ZnO{\cdot}2B_2O_3$, and $5ZnO{\cdot}2SiO_2$, on the densification, microstructural evolution, and microwave properties of the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics was examined. Results indicate that among the fluxes studied, $Bi_2O_3$, $B_2O_3$, and $Li_2CO_3$ could effectively reduce the sintering temperature of 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics through liquid phase sintering, while retaining the hexagonal structure and the microwave dielectric properties. The best results were obtained for the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ with the additions of 5 wt% $Bi_2O_3$ sintered at 900 °C ($\varepsilon_r$: 54.7, $Qf_r$: 1323, and $\tau_f$:183.3 ppm/°C), 10 wt% $B_2O_3$ sintered at 1100 °C ($\varepsilon_r$: 54.4, $Qf_r$: 3448, and $\tau_f$: 254.5 ppm/°C), and 5 wt% $Li_2CO_3$ sintered at 950 °C ($\varepsilon_r$: 43.7, $Qf_r$: 2501, and $\tau_f$: −29.8 ppm/°C).

## 1. Introduction

Barium titanate, $BaTiO_3$, based ceramics, which are commonly recognized as cornerstone of electroceramics, find applications in capacitors, positive temperature coefficient of resistance (PTCR) thermistors, chemical sensors, and piezoelectric devices. Most research to date has focused on the low-temperature tetragonal polymorph (t-$BaTiO_3$), due to the fact that it possesses the ferroelectric properties and the high dielectric constant at room temperature ($\varepsilon_r \approx 1000$–$2000$). Hexagonal $BaTiO_3$ (6h-$BaTiO_3$) polymorph is reported to be thermodynamically stable above 1460 °C according to the BaO–$TiO_2$ phase diagram [1]. Yet, it is kinetically stabilized at room temperature by many routes such as rapid quenching to room temperature after sintering at >1460 °C in air [1], or sintering at above 1300 °C in reducing atmosphere [2,3], and also by sintering of acceptor-doped $BaTiO_3$ in air [4–6]. For the latter two routes, the formation temperature of the 6h-$BaTiO_3$ is well below the $h \rightarrow c$ phase transformation temperature, 1460 °C [5].

Recently, doped 6h-$BaTiO_3$ ceramics were reported as potential candidates for use in dielectric resonators [6–9]. Wang et al. [8,9] investigated the microwave properties of doped 6h-$BaTiO_3$ ceramics and found that the best results were obtained for the composition of 6h-$Ba(Ti_{0.65}Mn_{0.35})O_3$ ($\varepsilon_r$: 41.2, $Qf_r$: 14300, and $\tau_f$:18.6 ppm/°C). However, similar to common microwave ceramics, doped 6h-$BaTiO_3$ ceramics require a high sintering temperature of greater than 1300 °C, which restricts the possibility of cofiring with other components. Up to now, no report has been found in the literature regarding the low sintering temperature of hexagonal $BaTiO_3$ ceramics. It is thus our motivation to reduce the sintering temperature of Mn-doped 6h-$BaTiO_3$ below 1000 °C while retaining the hexagonal structure and microwave dielectric properties.

In the present study, $Ba(Ti_{1-x}Mn_x)O_3$ with $x = 0.15$ [$Ba(Ti_{0.85}Mn_{0.15})O_3$] was used as host material since the pure form of hexagonal phase can be obtained at a calcination temperature of 1100 °C. The host material was then mixed with small amounts of common sintering aids, including $Bi_2O_3$, $B_2O_3$, $BaSiO_3$, $Li_2CO_3$, CuO, $V_2O_5$, $5ZnO{\cdot}2B_2O_3$, and $5ZnO{\cdot}2SiO_2$ [10–16], and followed by sintering at different temperatures. The effects of sintering aids on the densification, microstructural evolution, and microwave properties of the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics were examined and discussed.

## 2. Experimental procedure

$Ba(Ti_{0.85}Mn_{0.15})O_3$ powders were prepared by a solid-state reaction technique. High-purity (>99.9% purity) $TiO_2$, $BaCO_3$, and $MnCO_3$ (Merck, reagent grade) were used as raw materials. Oxides based on the compositions of $Ba(Ti_{0.85}Mn_{0.15})O_3$ were mixed and milled in methyl alcohol solution using polyethylene jars and zirconia balls for 24 h, and then dried at 80 °C in an oven overnight. After drying, the powders were calcined at 1100 °C for 4 h. Phase identification on the calcined powders was performed using X-ray diffraction (XRD, Rigaku DMX-2200). The calcined $Ba(Ti_{0.85}Mn_{0.15})O_3$ powder was mixed with different amounts of sintering aids

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($Bi_2O_3$, $B_2O_3$, $BaSiO_3$, $Li_2CO_3$, $5ZnO{\cdot}2B_2O_3$, $5ZnO{\cdot}2SiO_2$) and remilled in methyl alcohol for 24 h. The powders after drying were determined to have a particle size of ≈0.7 μm by light scattering (Horiba, LA-950). The powders were added with 5 wt% of a 15% PVA solution and pressed into disc-shaped compacts at a uniaxial pressure of 120 MPa. The obtained samples were then heat-treated at 550 °C for 2 h to eliminate PVA, followed by sintering in the temperatures ranging from 800 to 1200 °C for 2 h at a heating rate of 10 °C/min.

The densities of the samples were measured by a liquid displacement method. X-ray diffraction (Rigaku DMX-2200) with monochromatic Cu-Kα radiation was performed for the phase identification of the ground-sintered ceramic powders. Scanning electron microscopy (SEM; Hitachi S4700) and energy-dispersive spectroscopy (EDS) were performed on the sintered surfaces to characterize microstructures. The dielectric constants ($\varepsilon_r$) and unloaded $Q$ values at microwave frequencies were measured in the $TE_{01\delta}$ mode by a Hakki and Coleman method [17] with a network analyzer (HP 8722ES). The temperature coefficient of the resonance frequency ($\tau_f$) was measured in a low-temperature Delta Design box furnace in the temperature range from 25 to 85 °C.

## 3. Results and discussion

The host material of $Ba(Ti_{0.85}Mn_{0.15})O_3$ powders, prepared from solid-state reaction at 1100 °C, consists of hexagonal (6h) $BaTiO_3$ structure [space group of $P6_3/mmc$ (No. 194), and lattice parameters of $a = 0.572$ nm and $c = 1.396$ nm (JCPDS 34-0129)], though a very trace amount of 12R polytype [similar to trigonal-$BaFeO_3$ structure (JCPDS 74-0646, No. 166, $R\bar{3}m$, $a = 0.569$ nm, $c = 2.801$ nm] was

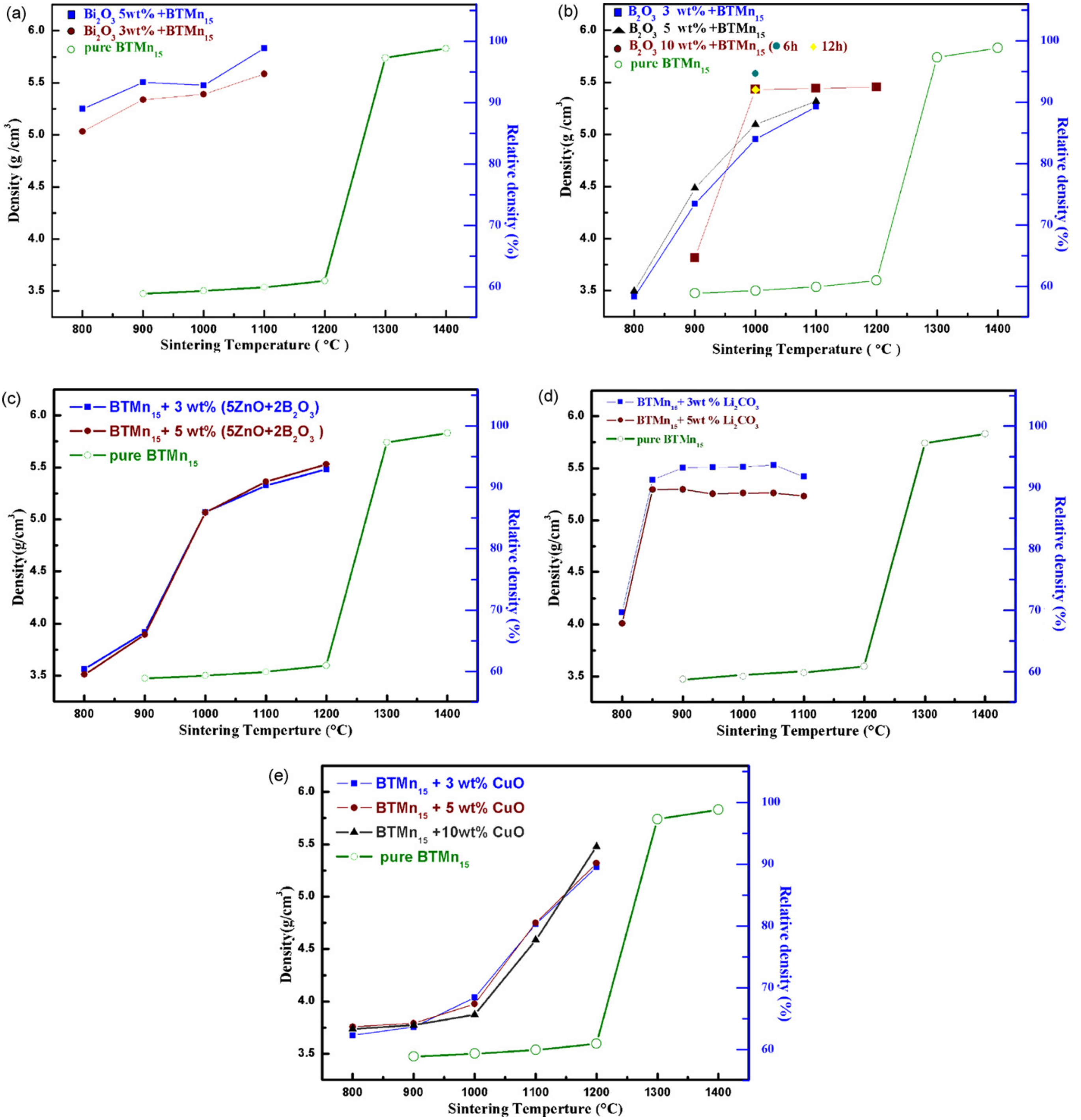

**Fig. 1.** Sintered densities of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of (a) $Bi_2O_3$, (b) $B_2O_3$, (c) $5ZnO{\cdot}2\ B_2O_3$, (d) $Li_2CO_3$, and (e) CuO, sintered at various temperatures.

also observed [18]. When the host material was sintered, hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with density of 5.72 g/cm$^3$ (97.6% of theoretical density) can be achieved at the sintering temperature of ≈1300 °C, which is similar to that of common tetragonal $BaTiO_3$ ceramics. Average grain size of ≈2.1 μm, evaluated based on the SEM micrographs by a linear intercept method [19], was obtained. The $\varepsilon_r$, $Qf$, and $\tau_f$ values of the host material sintered at 1300 °C are 61.1, 10,010, and 207.0 ppm/°C, respectively.

In order to lower the sintering temperature of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$, several fluxes including $Bi_2O_3$, $B_2O_3$, $BaSiO_3$, $Li_2CO_3$, CuO, $V_2O_5$, $5ZnO{\cdot}2B_2O_3$, and $5ZnO{\cdot}2SiO_2$, commonly used in tetragonal $BaTiO_3$ were selected in this study. The sintered densities of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of various fluxes sintered at different temperatures are shown in Fig. 1. Hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with most of the flux additions can be efficiently densified at temperatures less than 1200 °C, except those ceramics with the additions of $5ZnO{\cdot}2SiO_2$, $BaSiO_3$, and $V_2O_5$, which indicate a negligible densification and therefore were not further examined. XRD patterns and surface SEM micrographs on the selected densified $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of various fluxes are shown in Figs. 2 and 3, respectively. Microwave dielectric properties of $\varepsilon_r$ and $Qf_r$ values for hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of various fluxes sintered at different temperatures are shown in Fig. 4 and a selected list of the results are indicated in Table 1.

### 3.1. Hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ with addition of $Bi_2O_3$

Results shown in Fig. 1(a) indicate that an addition of 5 wt% $Bi_2O_3$ significantly increases the density of $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic at the sintering temperature as low as 900 °C, which is almost 400 °C lower than that of the pure $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic. A pure 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with a little amount of $Bi_2O_3$ phase was obtained with the disappearance of the 12R-$BaFeO_3$ polytype structure, as shown in Fig. 2(a). Density of 5.83 g/cm$^3$ (99.5% theoretical) can be achieved at sintering temperature of 1100 °C. It appears that the grain growth was inhibited by the addition of $Bi_2O_3$ during sintering. An average grain size of ≈0.8 μm was observed at the sintering temperature of 900 °C for host material with 5 wt% $Bi_2O_3$. Carefully examining the SEM micrograph, a second phase was observed at the grain boundaries. The effect of $Bi_2O_3$ addition on the microstructural evolution of hexagonal $BaTiO_3$ is similar to that observed in the tetragonal $BaTiO_3$, reported by Kumar et al. [14].

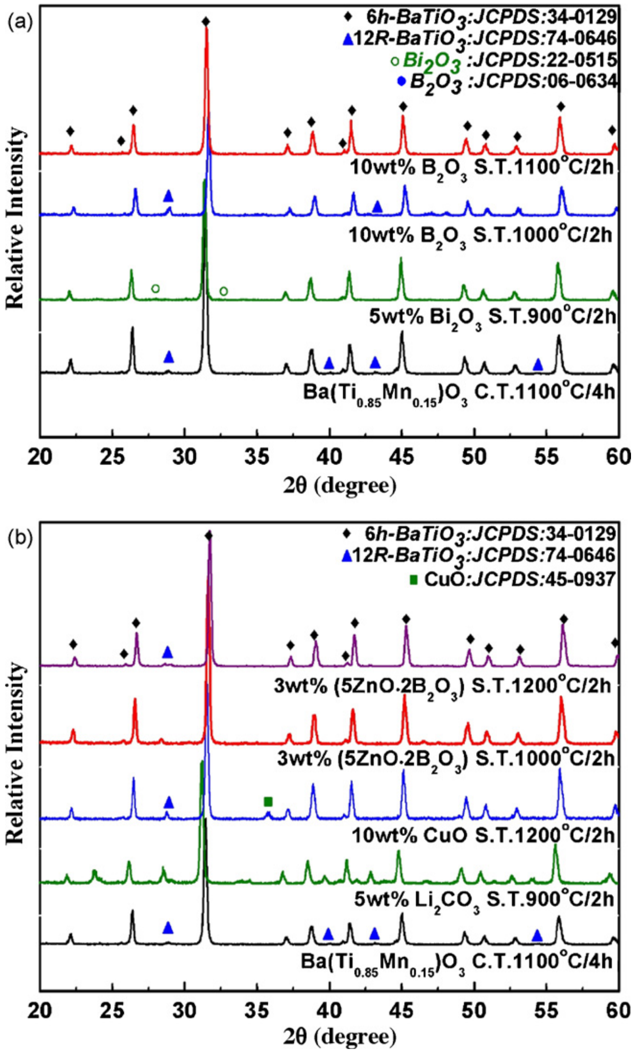

**Fig. 2.** XRD patterns of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of (a) 5 wt% $Bi_2O_3$ sintered at 900 °C and 10 wt% $B_2O_3$ sintered at 1000 °C, 1100 °C, and (b) 3 wt% $5ZnO{\cdot}2B_2O_3$ sintered at 1000 °C, 1200 °C, 5 wt% $Li_2CO_3$ sintered at 900 °C, and 10 wt% CuO sintered at 1200 °C.

Fig. 4(a) shows the microwave dielectric properties of the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of 3 and 5 wt% $Bi_2O_3$. Both the dielectric constant and the quality factor are diluted by the addition of $Bi_2O_3$, but change in the temperature coefficient of the resonance frequency is trivial. Dielectric constant increases with the sintering temperature and the amount of $Bi_2O_3$, and is in turn strongly correlated to the trends of sintering densities. Generally the $Qf$ value decreases with the sintering temperature, which is due to the interaction of $Bi_2O_3$ and host material at high temperatures

**Table 1**
A selected list of microwave dielectric properties for fluxed and sintered hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics.

| Sintering aid (wt%) | Sintering temperature (°C) | Sintered density (g/cm$^3$) | Microwave properties | | | |
|---|---|---|---|---|---|---|
| | | | $f$ (GHz) | $\varepsilon_r$ | $Qf$ (GHz) | $\tau_f$ (ppm/°C) |
| – | 1300 | 5.70 | | 61.1 | 10010 | 207.0 |
| 3 wt% $Bi_2O_3$ | 900 | 5.34 | 7.2 | 50.3 | 1241 | 119.7 |
| 5 wt% $Bi_2O_3$ | 900 | 5.51 | 8.1 | 54.7 | 1323 | 183.3 |
| 10 wt% $B_2O_3$ | 1000 | 5.43 | 6.9 | 52.1 | 1770 | 271.7 |
| 3 wt% $5ZnO{\cdot}2B_2O_3$ | 1100 | 5.44 | 6.8 | 54.4 | 3448 | 254.5 |
| | 1000 | 5.01 | 6.5 | 55.8 | 1960 | 197.2 |
| 3 wt% | 1200 | 5.48 | 6.7 | 54.5 | 4837 | 183.2 |
| $Li_2CO_3$ | 850 | 5.39 | 6.9 | 51.4 | 1391 | – |
| 5 wt% $Li_2CO_3$ | 950 | 5.51 | 7.0 | 51.5 | 1352 | 49.4 |
| | 850 | 5.29 | 7.9 | 43.0 | 1536 | – |
| 10 wt% CuO | 950 | 5.25 | 7.9 | 43.7 | 2501 | –29.8 |
| | 1200 | 5.48 | 7.1 | 51.0 | 4586 | 152.3 |

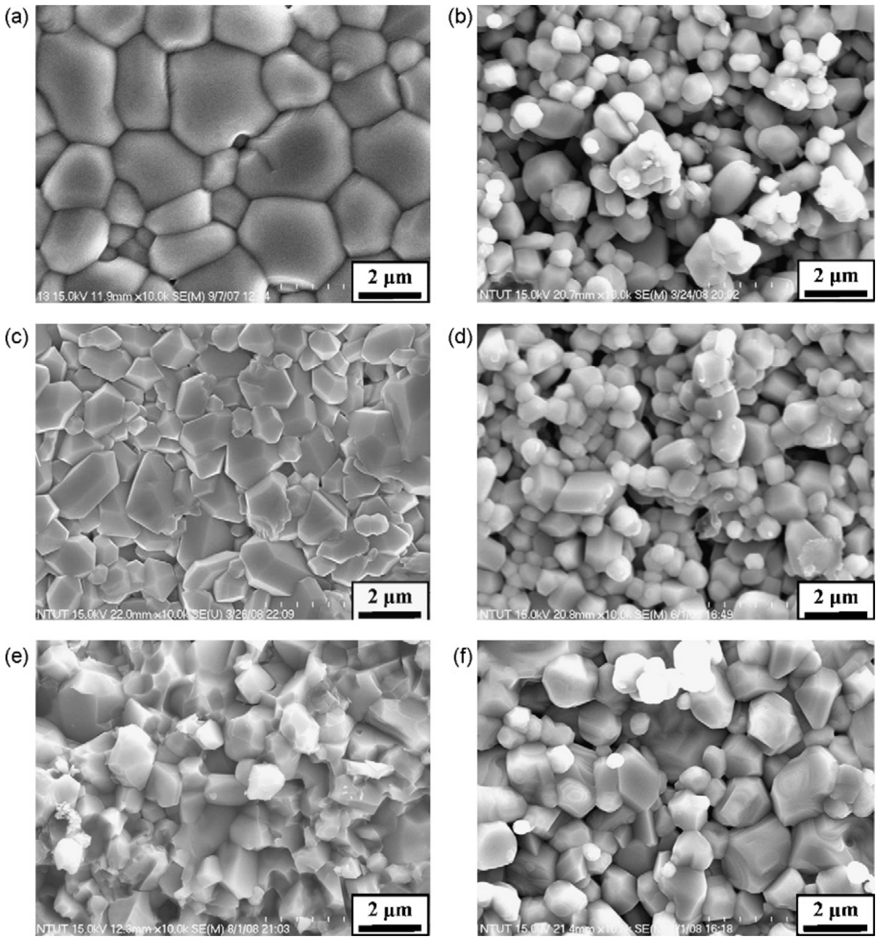

**Fig. 3.** Surface SEM micrographs of (a) pure hexagonal Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ ceramic sintered at 1300 °C, and that with additions of (b) 5 wt% $Bi_2O_3$ sintered at 900 °C, (c) 10 wt% $B_2O_3$ sintered at 1000 °C, (d) 3 wt% $5ZnO{\cdot}2B_2O_3$ sintered at 1000 °C, (e) 3 wt% $Li_2CO_3$ sintered at 900 °C, and (f) 10 wt% CuO sintered at 1200 °C.

that poisons the quality factor. The best results obtained in this study were $\varepsilon_r$ of 54.7, *Qf* of 1323, and $\tau_f$ of 183.4 ppm/°C.

### 3.2. Hexagonal Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ with addition of $B_2O_3$

Fig. 1(a) shows the sintered density versus sintering temperature for the host material with various amounts of $B_2O_3$. Addition of $B_2O_3$ significantly reduces the densification temperature of the host material. The sintered densities of the samples increase with the extent of $B_2O_3$. In order to reduce the sintering temperature to below 1000 °C, 10 wt% of $B_2O_3$ was added into the post-calcined Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ powders. Density of 5.4 g/cm$^3$ for the ceramic was obtained. Increasing the soaking time from 2 to 6 h has an obvious change in the density (5.58 g/cm$^3$). However, further increase in the soaking time results in reduction of sintered density, due to the evaporation of $B_2O_3$ and the trapped porosity [15]. For the sintering temperatures below 1100 °C, a minor phase of 12R polytype structure and a second phase of $B_2O_3$ were present in the ceramics [Fig. 2(a)]. Very dense microstructure with an average grain size of 1.9 µm for host material with 10 wt% $B_2O_3$ sintered at 1000 °C for 6 h was seen, as shown in Fig. 3(c).

The microwave dielectric properties of the host materials with 10 wt% $B_2O_3$ addition and sintered at various temperatures are shown in Fig. 4(c). The $\varepsilon_r$, *Qf*, and $\tau_f$ values for the ceramics sintered at 1000 and 1100 °C are 52.1, 1770, and 271.7 ppm/°C, and 54.4, 3448, and 254.5 ppm/°C, respectively. Increasing the soaking time at 1000 °C does not further improve the microwave dielectric properties of the ceramics.

### 3.3. Hexagonal Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ with addition of $Li_2CO_3$

Among the fluxes studied, $Li_2CO_3$ is the most effective sintering aid for the hexagonal Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ ceramic, similar to that observed in tetragonal $BaTiO_3$ [20–22]. Maximum sintered densities were achieved at the sintering temperatures of 900 and 850 °C for the addition of 3 and 5 wt% $Li_2CO_3$, respectively. Above the temperature at which maximum density was achieved, the sintered density levels off. The sintered density decreases with increasing the $Li_2CO_3$ content due to the light weight nature of Li compounds. Only 6h- and 12R-Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ phases are present in the XRD patterns and no detectable second phase was observed, as shown in Fig. 2(b). Grain size of the Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ ceramics sintered with $Li_2CO_3$ increases significantly with sintering temperature and the content of the $Li_2CO_3$, which is commonly reported in the liquid phase sintering of ceramics. Fig. 3(c) shows the dense microstructure of the Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ ceramic with 3 wt% of $Li_2CO_3$ sintered at 900 °C, in which the average grain size is 1.6 µm.

As shown in Fig. 4(c), the change in dielectric constant of the Ba($Ti_{0.85}Mn_{0.15}$)$O_3$ ceramics with $Li_2CO_3$ additions is insignificant, while it follows the path of sintered density versus temperature profile very well. The dielectric constants of ceramics with 3 and 5 wt% of $Li_2CO_3$ and sintered at 850 °C are 51.4 and 43, respectively. Clearly, dielectric constants of the ceramics were diluted by the presence of the second phase. It may be attributed to the $LiTiO_2$ phase, similar to that reported in the study of tetragonal $BaTiO_3$ with addition of Li compounds by Randall et al. [20] and Lin and Wu [21]. The *Qf* values for this system are around 2000, though a

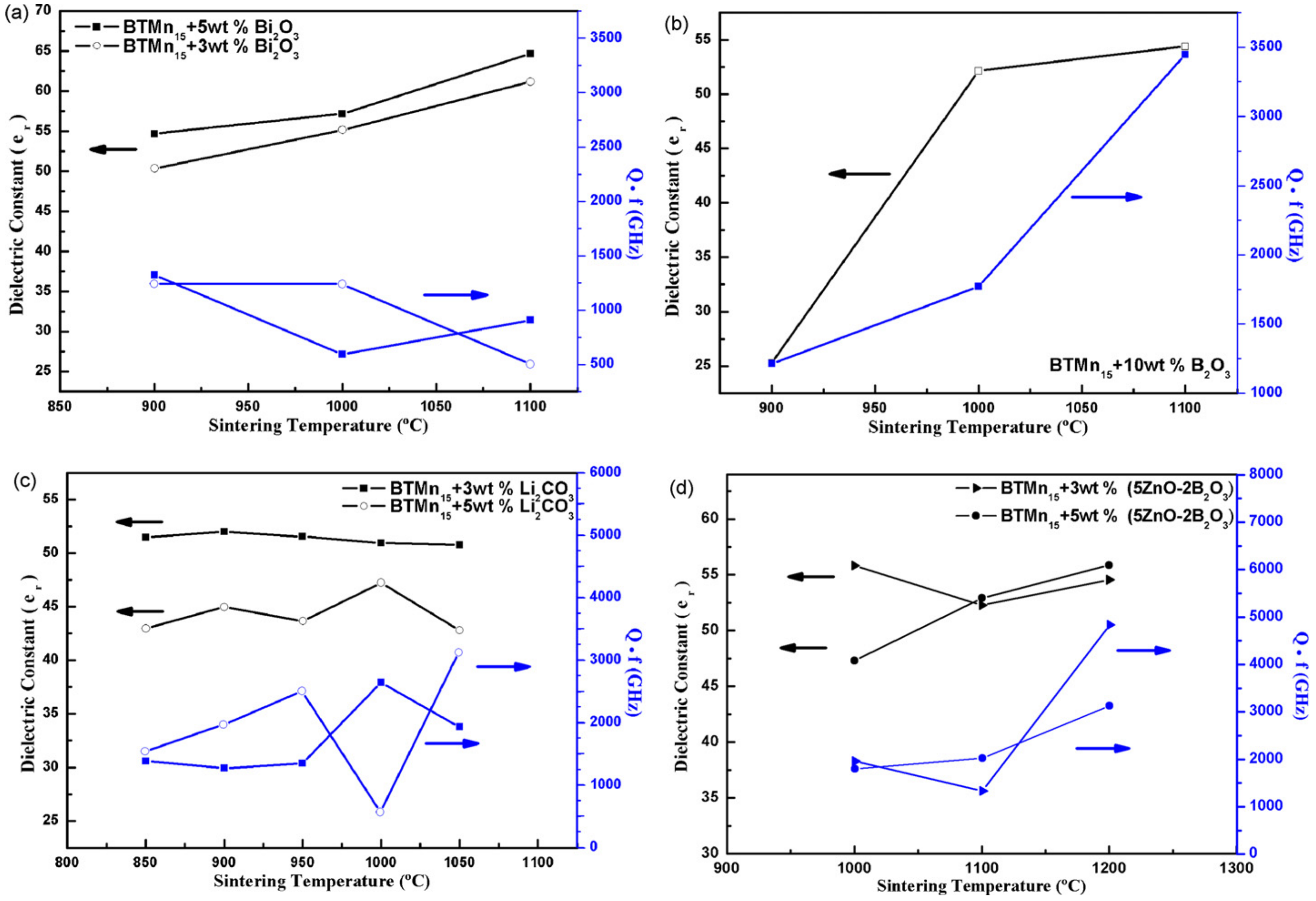

**Fig. 4.** Microwave dielectric properties of $\varepsilon_r$ and $Qf_r$ values for hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics with additions of (a) $Bi_2O_3$, (b) $B_2O_3$, (c) $5ZnO{\cdot}2\ B_2O_3$, and (d) $Li_2CO_3$, sintered at various temperatures.

variation exists. The $\tau_f$ values for the ceramics with 3 and 5 wt% of $Li_2CO_3$ and sintered at 950 °C are 49.4 and −29.8 ppm/°C (Table 1), respectively, which are different from those ceramics with additions of other fluxes that do not affect the $\tau_f$ value of the sintered ceramic. The reduction in $\tau_f$ value associated with the $Li_2CO_3$ addition may be due to the incorporation of $Li^+$ ions into the B-sites of $Ba(Ti_{0.85}Mn_{0.15})O_3$ structures, similar to that reported in the low-temperature phases (tetragonal and cubic) of $Ba(Ti_{1-x}, Li_x)O_3$ [22].

### 3.4. Hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ with addition of $5ZnO{\cdot}2B_2O_3$

Fig. 1(c) shows the sintered density of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with 3 and 5 wt% $5ZnO{\cdot}2B_2O_3$ glass at different sintering temperatures. It seems that the extent of $5ZnO{\cdot}2B_2O_3$ glass does not have a strong effect on the densification, as observed in other microwave materials [15,23]. The sintered density increases with increasing sintering temperature, in which the density of 5.54 g/cm$^3$ was obtained at the sintering temperature of 1200 °C. XRD patterns in Fig. 2(b) show the presence of 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ phase with trace amount of 12R polytype. No other phase is visible in XRD patterns. Microstructure with an average grain size of 0.8 μm and a wide grain size distribution was obtained for the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with 3 wt% $5ZnO{\cdot}2B_2O_3$ glass sintered at 1000 °C. Fig. 4(d) shows the $\varepsilon_r$ and $Qf$ values of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with 3 and 5 wt% $5ZnO{\cdot}2B_2O_3$ glass at different sintering temperatures. Best results are obtained in the sample containing 3 wt% $5ZnO{\cdot}2B_2O_3$ glass and sintered at 1200 °C, in which the $\varepsilon_r$, $Qf$, and $\tau_f$ values are 54.5, 4837, and 183.2 ppm/°C, respectively, as listed in Table 1. The microwave dielectric properties are closely correlated to the density of the $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic. The small effect of $5ZnO{\cdot}2B_2O_3$ glass on the densification behavior and microwave dielectric properties of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic implies only little chemical interaction between the glass and the host material.

### 3.5. Hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ with addition of CuO

CuO is a common sintering aid for microwave materials, which has a melting point of 1446 °C. Liquid phase was generated at high temperatures due to the interaction between CuO and $Cu_2O$. Densification of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with 3, 5, and 10 wt% CuO at different sintering temperatures is shown in Fig. 1(e). The sintered density increases with increasing sintering temperature, but the extent of CuO does not seem to affect the densification. The results indicated that density of 5.3 g/cm$^3$ (about 93% theoretical density of pure $BaTiO_3$) was achieved at sintering temperature of 1200 °C. The effect of the CuO addition on the densification of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics is limited. XRD results [Fig. 2(b)] indicate a major hexagonal phase, a minor phase of 12R polytype structure, and a trace amount of CuO phase in the ceramics. $BaCuO_2$, a second phase observed in the literature [16], was not found in this study. Fig. 3(f) shows the microstructure of the $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic with 10 wt% CuO and sintered at 1200 °C, which has an average grain size of 1.0 μm, and its dielectric properties are listed in Table 1. The $\varepsilon_r$, $Qf$, and $\tau_f$ values for the ceramics are 51.0, 4586, and 152.3 ppm/°C, respectively. Similar to

$5ZnO{\cdot}2B_2O_3$ glass addition, the microwave dielectric properties are closely correlated to density of the $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramic.

From the results discussed above, most fluxes used as sintering aids in tetragonal phase of $BaTiO_3$ also effectively reduce the sintering temperature of hexagonal $Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics through liquid phase sintering, without loosing the microwave dielectric properties, particularly for the specimens with $Bi_2O_3$ or $Li_2CO_3$ additions. The effectiveness of the flux is closely related to the wettability of liquid on the host material and the volume fraction of the liquid phase during sintering [24], which is in turn determined on the level of chemical interaction between the flux and the host material. Similar to other microwave dielectric ceramics, such as $Ba_2Ti_2O_9$, $Ba(Mg_{1/3}Ta_{2/3})O_3$, etc., sintered with fluxes, the $\varepsilon_r$ values are diluted by the presence of the second phase at the grain boundaries, and the *Qf* values are degraded by the chemical interaction of the host materials and the fluxes, which reduces the ordering of the structure or decreases the chemical purity. The $\tau_f$ values of the fluxed and sintered ceramics are dependent on the substitutions of the foreign ions which alters the tilt angle of the $TiO_6$-octahedron.

## 4. Conclusion

In this study, 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ with additions of various sintering aids, including $Bi_2O_3$, $B_2O_3$, $BaSiO_3$, $Li_2CO_3$, CuO, $V_2O_5$, $5ZnO{\cdot}2B_2O_3$, and $5ZnO{\cdot}2SiO_2$, were sintered at different temperatures. The effects of sintering aids on the densification, microstructural evolution, and microwave properties of the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics were examined. Among the fluxes studied, $Bi_2O_3$, $B_2O_3$, and $Li_2CO_3$ were found to be effective sintering aids for the 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics. Results indicate that the best results were obtained for the compositions of 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ with the additions of 5 wt% $Bi_2O_3$ sintered at 900 °C ($\varepsilon_r$: 54.7, $Qf_r$: 1323, and $\tau_f$:183.3 ppm/°C), 10 wt% $B_2O_3$ sintered at 1100 °C ($\varepsilon_r$: 54.4, $Qf_r$: 3448, and $\tau_f$: 254.5 ppm/°C), and 5 wt% $Li_2CO_3$ sintered at 950 °C ($\varepsilon_r$: 43.7, $Qf_r$: 2501, and $\tau_f$: −29.8 ppm/°C). These results suggest that 6h-$Ba(Ti_{0.85}Mn_{0.15})O_3$ ceramics can be sintered with fluxes at temperatures lower than 1100 °C through liquid phase sintering, while retaining its hexagonal structure and microwave dielectric properties.

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