

DIELECTRIC PROPERTIES OF GLASS CERAMIC COMPOSITES FABRICATED VIA MICROWAVE TECHNIQUE

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Abstract

The investigations and enhancement of dielectric ceramics have been studied for decades in order to improve their performance of sustainable management in energy. To increase dielectric constant, dielectric breakdown strength and to decrease dielectric loss have been generally focused. In this study, $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$, using as ceramics phase, and borosilicate glass powder were fabricated to glass ceramic composites with different concentration via microwave heating technique. X-ray diffraction technique and Raman spectroscopy revealed the crystalline phase existence in the glass ceramic composites. The results were also confirmed by Scanning Electron Microscope. Moreover, as the content of ceramic phase increased it was found that the dielectric constant increased and dielectric loss decreased.

Keywords: Dielectric; Glass Ceramics; Microwave; Sustainable Energy; Titanium Dioxide

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Introduction

Recently, Sustainable Development Goals (SDGs) have garnered significant interest worldwide as countries aim to protect and preserve the environment. Although energy management is not explicitly categorized as one of the 17 goals, it serves as a crucial tool in driving the success of many of these goals. The utilization of renewable energy technology plays an important role of energy management to promote sustainable living, however, it requires excellent energy storage devices. Consequently, the development of high energy density storage devices has been attracted. Dielectric ceramic capacitors have been interested as the promising candidate for high energy density storage devices due to their strong advantages, including high power density resulting in fast charge and discharge, long life-cycle, and environmental durability (Yao *et al.*, 2017; Sriphan *et al.*, 2019; Abdel Maksoud *et al.*, 2021; Charoonsuk *et al.*, 2021; Prasatkhetragarn *et al.*, 2022; Triamnak *et al.*, 2023). High dielectric oxide ceramics have been extensively studied and enhanced due to their excellent dielectric constant and low dielectric loss. $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ (CCTO) (Chung *et al.*, 2004), doped- BaTiO_3 (Buscaglia *et al.*, 2006), doped NiO (Wu *et al.*, 2002; Wang *et al.*, 2013), $\text{Bi}(\text{M}', \text{M}'')\text{O}_3$ - BaTiO_3 (Raengthon *et al.*, 2012; Triamnak *et al.*, 2013; Triamnak *et al.*, 2014; Triamnak *et al.*, 2022), doped- TiO_2 (Pulphol *et al.*, 2022), etc. have been explored and reported their excellent dielectric properties. Among these oxide ceramics, doped- TiO_2 have gained high attention due to their typical dielectric constant over 10^4 with lower dielectric loss than 0.1. The prominent dielectric properties cause by the defects creating the insulating boundaries regions and semiconducting grains. Moreover, this phenomenon was also observed in many acceptor-donor co-doped TiO_2 such as Bi-Nb co-doped- TiO_2 , Sm-Nb co-doped- TiO_2 , Ga-Nb co-doped- TiO_2 , Zn-Nb co-doped- TiO_2 , In-Ta co-doped- TiO_2 , Mg-W co-doped- TiO_2 , In-W co-doped- TiO_2 , and Ni-Nb co-doped- TiO_2 , (Cheng *et al.*, 2015; Wei *et al.*, 2015; Song *et al.*, 2016; Dong *et al.*, 2017; Guo *et al.*, 2018; Pulphol *et al.*, 2022). Among these co-doped- TiO_2 ceramics, $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ demonstrated the outstanding candidate because of the ability to optimize between high dielectric constant, low dielectric loss, and raw materials affordability.

The strategy to improve high energy density storage ceramics has focused on increasing dielectric constant, enhancing dielectric breakdown strength, and decreasing dielectric loss. Generally, introduction of dopants into dielectric ceramics

has been widely performed in order to improve dielectric constant and dielectric loss. Unfortunately, such improvement frequently deteriorates dielectric breakdown strength of the dielectric ceramics materials, thereby reducing energy storage performance. Therefore, the enhancement of dielectric breakdown strength is also important. Amorphous materials, such as glass and polymers, generally exhibit excellent dielectric breakdown strength, however, they often display poor dielectric constant. Combining high dielectric ceramics with amorphous materials could result in the optimization of dielectric properties, tuning them for high energy density applications.

In this study, glass ceramic composites comprising borosilicate glass and $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic were fabricated. The microwave heating technique was utilized because of its fast heating and cooling processes, which reduce the dissolution of ceramic particles in the glass matrix. A systematic study of the content of the ceramic phase on the properties of the glass ceramics composites samples were investigated and discussed.

Experimental

Materials

Borosilicate glass powder was prepared via the melt quenching method. The raw materials with purity of 99.9% were stoichiometrically weighted and mixed via ball milling for 8 h to obtain the glass composition of $60\text{SiO}_2 \cdot 15\text{CaO} \cdot 10\text{B}_2\text{O}_3 \cdot 5\text{Al}_2\text{O}_3 \cdot 4\text{Na}_2\text{O} \cdot 3\text{MgO} \cdot 3\text{K}_2\text{O}$. The mixture was heated in an alumina crucible at $1,500^\circ\text{C}$ for 8 h and poured into graphite molds at room temperature to obtain a glass ingot. After the glass ingot cooled, it was fractured and ball milled to obtain glass powder.

The ceramic powder of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ was prepared by conventional solid state reaction. The reagents of TiO_2 , Nb_2O_5 , and NiO with purity of 99.9% were stoichiometrically weighted and ball milled for 8 h in ethanol. After overnight drying, the mixture was calcined in an alumina crucible at $1,400^\circ\text{C}$ for 4 h. The calcined powder was then ball milled again to obtain fine powder for the fabrication of glass ceramic composites.

Glass Ceramic Composites Preparation

The glass ceramic composites samples were prepared with concentrations ranging from 5.30 wt% of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic. The mixture of borosilicate glass powder and $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$

ceramic powder was accurately weighted, mixed and ground in an alumina mortar for 20 min to ensure homogeneity. After mixing, the powder was uniaxially hydraulic compressed into pellets with a force of 2,000 kN for 3 min. In order to sinter the samples, the pellets were placed into microwave kiln and then into the microwave oven (Samsung MS23K3513AW microwave oven). The samples were heated via microwave at an operating power of 800 watts for 25 min. Subsequently, the properties of fabricated samples were then characterized.

Characterizations

The crystal structure of the glass ceramic composites was examined by X-ray diffraction technique with $\text{CuK}\alpha$ ($\lambda = 1.5406 \text{ \AA}$) X-ray source at a current of 20.0 mA and a voltage of 30.0 kV (XRD, LabX XRD-6100 Diffractometer, Shimadzu, Kyoto, Japan). The glass ceramic composites were ground by the alumina mortar for 15 min to obtain powder form for the measurement. The morphology of the fractured surface of the pellets was carried out by Scanning Electron Microscope (SEM, TM303 Hitachi). The UV-Vis absorbance of the samples was characterized by UV-Vis spectrophotometer (Shimadzu, UV-3600). The samples were measured over the wavelength ranging from 300 nm to 800 nm. The dielectric properties were investigated by LCR meter at room temperature (HP-4284A, Hewlett-Packard, Palo Alto, CA). The glass ceramic composites were polished to the disc shape with thickness of 1 mm and silver pasted as the electrode before the measurement.

Results and Discussion

Side-view images of the glass ceramic composites after being microwave heated for 25 min was depicted in Figure 1. It can be observed that the glass ceramic composites exhibited a dome shape across all concentrations. The outer surface of the pellets

appeared shiny, however, they were all opaque. With the addition of 5 wt% of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic the sample, labeled as “doped TiO_2 5 wt%”, displayed a light yellow-white color. The increase in $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic concentration resulted in a more yellow hue, similar to the color of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic powder. These changes in appearance briefly suggested that the $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ crystalline phase could persist within the glass matrix while the samples were melted by microwave heating.

Fractured surface of the glass ceramic composites were revealed by SEM techniques as shown in Figures 2 and 3. The observation revealed that there were spherical pores randomly spreading within the glass matrix in all samples. The pores initially might have existed as empty spaces between particles of glass powder. As the compressed glass pellets were subjected to heating in the microwave oven, the glass powder particles began to melt, and their mobility increased. Once the temperature reached a sufficiently high level, the molten glass powder particles fused together. Consequently, the empty spaces became trapped and transformed into spherical pores, aiming to reduce surface energy. Because of the rapid heating and cooling cycles characteristic of the microwave heating technique, the pores were unable to escape from the samples. Besides the pores, agglomerates of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ phase were also detected. The presence of crystalline $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ phase could also be attributed to the rapid heating and cooling features of the microwave technique, which reduce the dissolution of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ particles in the glass matrix. Thus, the ceramic particles were seen even when the addition of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ was as low as 5 wt%. In addition, the SEM images showing the fractured surface at 2000X magnification of the doped TiO_2 0 wt%, the doped TiO_2 5 wt%, and the doped TiO_2 30 wt% samples are presented in Figure 3. It should be noted that nucleation of crystalline phases was



Figure 1. Side view images of the glass ceramic composites with concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic ranging from 5-30 wt%

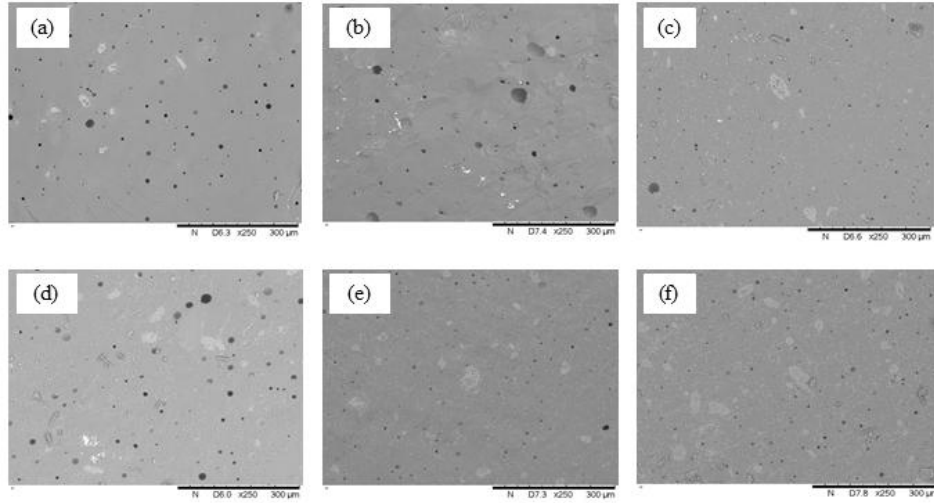


Figure 2. Fractured surface morphology of the (a) doped TiO_2 5 wt%, (b) doped TiO_2 10 wt%, (c) doped TiO_2 15 wt%, (d) doped TiO_2 20 wt%, (e) doped TiO_2 25 wt%, and (f) doped TiO_2 30 wt% glass ceramic composites at 200X magnification

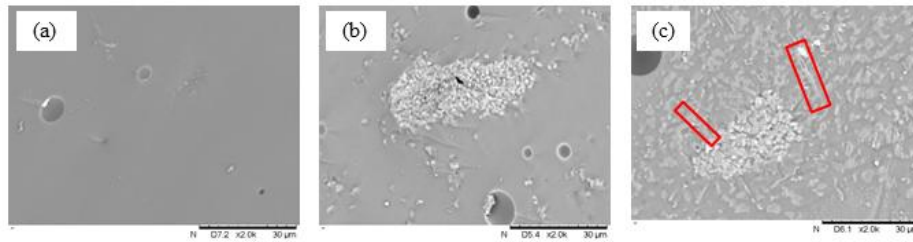


Figure 3. Fractured surface morphology of the (a) doped TiO_2 0 wt%, (b) doped TiO_2 5 wt%, and (c) doped TiO_2 30 wt% glass ceramic composites at 2000X magnification

not observed in the doped TiO_2 0 wt% sample as illustrated in Figure 3(a). It can be seen that another crystalline phase besides $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ particles appeared in the doped TiO_2 30 wt% sample, as marked by red rectangular in Figure 3(c), while this phase was not detected in the doped TiO_2 5 wt% sample, as shown in Figure 3(b). This could be due to the higher concentration of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic particles could act as the nucleating agent. The rod-like crystalline phase, hence, was nucleated and growth within the borosilicate glass matrix.

The crystal structure of the glass ceramic composites was carried out from the ground samples by XRD technique, as demonstrated in Figure 4. The sample without the addition of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic, labeled as the doped TiO_2 0 wt%, exhibited a broad pattern without any peak appearance, confirming the amorphous structure of the pure glass sample. Furthermore, with the addition of 5 wt% of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic,

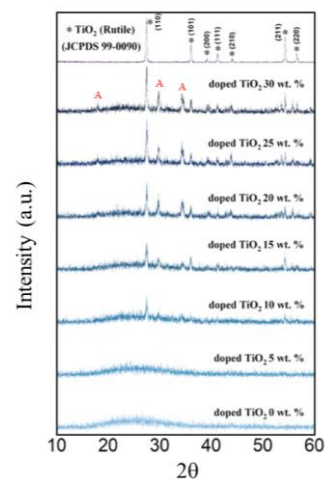


Figure 4. XRD pattern of the ground glass ceramic composites with concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic ranging from 0-30 wt%

the characteristic peaks of rutile were hardly detected. However, as the concentration of the $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic increased, the characteristic peaks of rutile became more pronounced, corresponding to JCPDS 99-0090. Moreover, not only the rutile phase but also a crystalline impurity phase was detected. These peaks appearances could be attributed to the anorthite phase as labeled as “A”, which could nucleate during heating of the samples (Kara and Stevens, 2002). These XRD results are in good agreement with the SEM results. It should be noted that a small hump of amorphous characteristics between 2θ of 15° - 35° was observed across all samples.

The observed results in SEM and XRD techniques ensure that glass ceramic composites can be successfully fabricated using rapid heating and cooling processes such as the microwave technique. Typically, when the glass matrix is melted using a convention heating technique in conventional furnaces it readily dissolves additional crystalline particles. Preserving these additional crystalline phases becomes challenging. Glass ceramic composites are, thus, often prepared by annealing in order to initiate self-nucleation of ceramic phases within the glass matrix compositions. This route is complicated due to various factors to control the crystalline phase appearance. Therefore, the rapid heating and cooling processes facilitated by the microwave techniques make the creation of glass ceramic composites more feasible and efficient. It is worth nothing that, although the induced impurity phase was still detected in this study, it could potentially be eliminated by using appropriate compositions in future research endeavors.

The UV-Vis absorption spectra, ranging between 350-700 nm, of the ground glass ceramic composites with concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic ranging from 0-30 wt% are shown in Figure 5(a). The doped TiO_2 0 wt% sample exhibited slight light absorption in the UV region, specifically in the range of 350-380 nm. The absorption in the UV region is the characteristic of the amorphous network within the borosilicate glass. However, minimal absorption was observed in the visible light region. As the concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic increased, the absorption in UV region became more pronounced. An absorption edge was detected at approximately 400 nm, attributed to the energy bandgap of the $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic that remains in the glass ceramic composites. In addition, slight absorption in the blue light region, ranging from 400 to 470 nm, was also detected. This absorption corresponds to the yellowish color of the samples,

due to the color of the $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic. To determine the energy bandgap of the samples, Tauc plot and Kubelka-Munk calculations were performed. The Tauc plot of the doped TiO_2 5 wt% sample is demonstrated in Figure 5(b). The energy bandgaps of the glass ceramic composites with various concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic are summarized in Table 1. It was found that as the concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic increased from 5-30 wt%, the energy bandgap decreased from 3.06-3.03 eV, respectively.

The dielectric properties of the glass ceramic composites samples were investigated at room temperature within a frequency range of 200 Hz to 1 MHz, as demonstrated in Figure 6. The dielectric constants of the samples approximately ranged from 15 to 20. As the concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic increased, the dielectric constants also increased. Moreover, it could also be observed that as the measuring frequency increased, the dielectric constant slightly decreased across the frequency range. These minor changes in dielectric constant across the frequency range are beneficial for various applications. Furthermore, the $\text{Tan}\delta$, representing dielectric loss, was low in

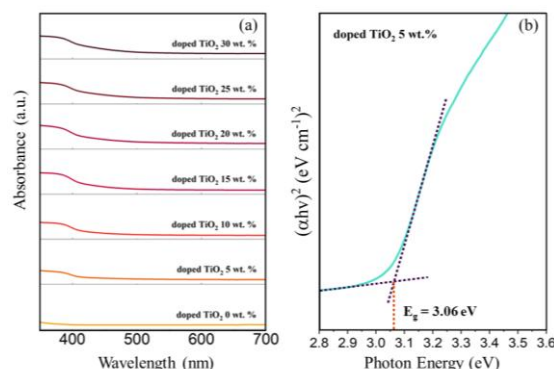


Figure 5. (a) Absorbance of UV-Vis spectra of the ground glass ceramic composites with concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic ranging from 0-30 wt% , and (b) Tauc plot of the doped TiO_2 5 wt% sample

Table 1. Energy band gap of the glass ceramic composites with various concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic

Samples	Band gap (eV)
doped TiO_2 5 wt%	3.06
doped TiO_2 10 wt%	3.05
doped TiO_2 15 wt%	3.04
doped TiO_2 20 wt%	3.04
doped TiO_2 25 wt%	3.04
doped TiO_2 30 wt%	3.03

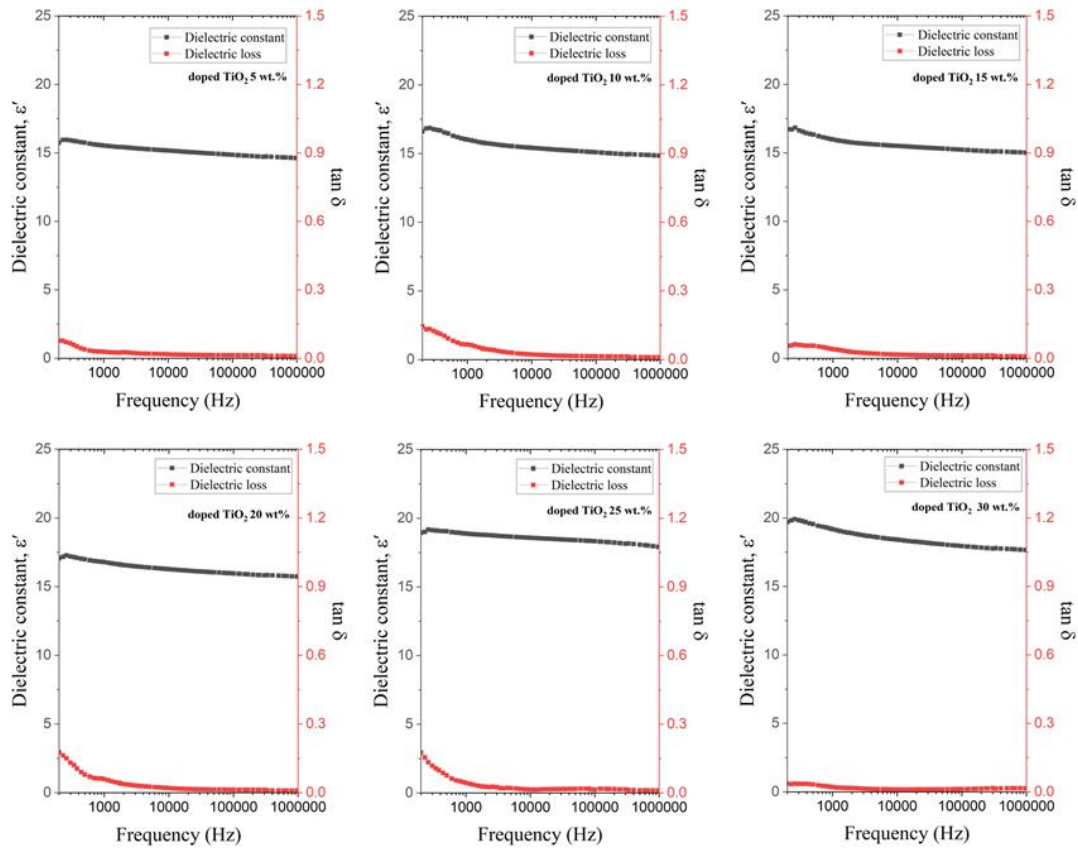


Figure 6. Dielectric properties of the glass ceramic composites pellets with concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic ranging from 5-30 wt%

all samples. This suggests good insulating characteristics, which could be indicative of good dielectric breakdown strength. The dielectric constants and $\tan \delta$ at 1 kHz of the glass ceramic composites with various concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramics are summarized in Table 2. Despite the dielectric constants of these glass ceramic composites samples not being as high as those of high dielectric ceramics, several advantages of these materials can still be highlighted. The minor changes in dielectric constants across a wide frequency range, the significant low dielectric loss, and the rapid fabrication processes are interesting discoveries.

Conclusions

To summarize, the glass ceramic composites consisting of borosilicate glass and $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic were successfully fabricated via the microwave heating technique utilization. The results of SEM and XRD demonstrated

Table 2. Dielectric properties of the glass ceramic composites with various concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic at 1 kHz

Samples	Dielectric Constant	$\tan \delta$
doped TiO_2 5 wt. %	15.54	0.03
doped TiO_2 10 wt. %	15.98	0.07
doped TiO_2 15 wt. %	16.02	0.04
doped TiO_2 20 wt. %	16.79	0.06
doped TiO_2 25 wt. %	18.88	0.04
doped TiO_2 30 wt. %	19.18	0.02

the presence of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic phase within the borosilicate glass matrix, although impurity crystalline phase was also observed. The energy bandgap of the glass ceramic composites samples slightly decreased with increasing concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic. The dielectric constants increased as the concentrations of $\text{Ti}_{0.98}(\text{Ni}_{0.01}, \text{Nb}_{0.01})\text{O}_2$ ceramic increased, while the dielectric loss remained consistently low. Even though the dielectric constant of these materials was not exceptional,

several advantages, such as the minor changes in dielectric constants across a wide frequency range, the significant low dielectric loss, and the rapid fabrication processes still illustrated their merit for various applications.

References

- Abdel Maksoud, M.I.A., Fahim, R.A., Shalan, A.E., Abd Elkodous, M., Olojede, S.O., Osman, A.I., Farrell, C., Al-Muhtaseb, A.H., Awed, A.S., Ashour, A.H., and Rooney, D.W. (2021). Advanced materials and technologies for supercapacitors used in energy conversion and storage: A review. *Environmental Chemistry Letters*, 19(1):375-439. <https://doi.org/10.1007/s10311-020-01075-w>
- Buscaglia, M.T., Viviani, M., Buscaglia, V., Mitoseriu, L., Testino, A., and Nanni, P., Zhao, Z., Nygren, M., Harnagea, C., Piazza, D., and Galassi, C. (2006). High dielectric constant and frozen macroscopic polarization in dense nanocrystalline BaTiO₃ ceramics. *Physical Review B*, 73(6):064114. DOI: 10.1103/PhysRevB.73.064114
- Charoonsuk, T., Muanghlua, R., Sriphan, S., Pongampai, S., and Vittayakorn, N. (2021). Utilization of commodity thermoplastic polyethylene (PE) by enhanced sensing performance with liquid phase electrolyte for a flexible and transparent triboelectric tactile sensor. *Sustainable Materials and Technologies*, 27:e00239 <https://doi.org/10.1016/j.susmat.2020.e00239>
- Cheng, X., Li, Z., and Wu, J. (2015). Colossal permittivity in ceramics of TiO₂ Co-doped with niobium and trivalent cation. *Journal of Materials Chemistry A*, 3(11):5805-5810. <https://doi.org/10.1039/C5TA00141B>
- Chung, S.-Y., Kim, I.-D., and Kang, S.-J.L. (2004). Strong nonlinear current-voltage behaviour in perovskite-derivative calcium copper titanate. *Nature Materials*, 3(11):774-778. <https://doi.org/10.1038/nmat1238>
- Dong, W., Hu, W., Frankcombe, T.J., Chen, D., Zhou, C., Fu, Z., Cândido, L., Hai, G., Chen, H., Li, Y., Withers, R.L., and Liu, Y. (2017). Colossal permittivity with ultralow dielectric loss in In + Ta co-doped rutile TiO₂. *Journal of Materials Chemistry A*, 5(11):5436-5441. <https://doi.org/10.1039/C6TA08337D>
- Guo, B., Liu, P., Cui, X., and Song, Y. (2018). Colossal permittivity and dielectric relaxations in Ti + Nb co-doped TiO₂ ceramics. *Ceramics International*, 44(11):12137 <https://doi.org/10.1016/j.ceramint.2018.03.255>
- Kara, A. and Stevens, R. (2002). Interactions between an ABS type leadless glaze and a biscuit fired bone china body during glaze firing. Part I: preparation of experimental phases. *Journal of the European Ceramic Society*, 22(7):1095-1102 [https://doi.org/10.1016/S0955-2219\(01\)00419-8](https://doi.org/10.1016/S0955-2219(01)00419-8)
- Prasatkhetragarn, A., Sareein, T., Triamnak, N., and Yimnirun, R. (2022). Dielectric and ferroelectric properties of modified-BaTiO₃ lead-free ceramics prepared by solid solution method. *Ferroelectrics*, 586(1):224-241. <https://doi.org/10.1080/00150193.2021.2014274>
- Pulphol, P., Pongampai, S., Charoonsuk, T., Vittayakorn, W., Muanghlua, R., and Vittayakorn, N. (2022). Intrinsic enhancement of permittivity with ultralow dielectric loss in donor-acceptor co-doped rutile TiO₂ ceramics. *Integrated Ferroelectrics*, 223(1):152-161. <https://doi.org/10.1080/10584587.2021.1964294>
- Raengthon, N., Sebastian, T., Cumming, D., Reaney, I.M., and Cann, D.P. (2012). BaTiO₃-Bi(Zn_{1/2}Ti_{1/2})O₃-BiScO₃ ceramics for high-temperature capacitor applications. *Journal of the American Ceramic Society*, 95:3554-3561. <https://doi.org/10.1111/j.1551-2916.2012.05340.x>
- Song, Y., Wang, X., Sui, Y., Liu, Z., Zhang, Y., Zhan, H., Song, B., Liu, Z., Lv, Z., Tao, L., and Tang, J. (2016). Origin of colossal dielectric permittivity of rutile Ti_{0.9}In_{0.05}Nb_{0.05}O₂: Single crystal and polycrystalline. *Sci. Rep.* 6 (1), 21478 <https://doi.org/10.1038/srep21478>
- Sriphan, S., Charoonsuk, T., Maluangnont, T., Vittayakorn, N. (2019). High-performance hybridized composited-based piezoelectric and triboelectric nanogenerators based on BaTiO₃/PDMS composite film modified with Ti_{0.8}O₂ nanosheets and silver nanopowders cofillers. *ACS Applied Energy Materials*, 2(5):3840-3850. <https://doi.org/10.1021/acsaem.9b00513>
- Triamnak, N., Brennecke, G.L., Brown-Shaklee, H.J., Rodriguez, M.A., and Cann, D.P. (2014). Phase formation of BaTiO₃-Bi(Zn_{1/2}Ti_{1/2})O₃ perovskite ceramics. *Journal of the Ceramic Society of Japan*, 122(1424):260-266 <https://doi.org/10.2109/jcersj2.122.260>
- Triamnak, N., Suttirungwong, S., Vittayakorn, N., Girdthep, S., and Khankrua, R. (2023). The Properties investigations of PLA/TiO₂ and PLA/Doped-TiO₂ composites films. *Polymer-Plastics Technology and Materials*, 62(12):1576-1586. <https://doi.org/10.1080/25740881.2023.2222818>
- Triamnak, N., Wongdamnern, N., Sareein, T., Ngamjarurojana, A., and Yimnirun, R. (2022). Lowering Synthesis Temperature of BaTiO₃-Bi(Zn_{0.5}Zr_{0.5})O₃ Ceramics by Salt Flux Assistance and Dielectric Properties Investigations. *Integrated Ferroelectrics*, 223(1):162-172. <https://doi.org/10.1080/10584587.2021.1964295>
- Triamnak, N., Yimnirun, R., Pokorny, J., and Cann, D.P. (2013). Relaxor Characteristics of the Phase Transformation in (1-x)BaTiO₃-xBi(Zn_{1/2}Ti_{1/2})O₃ Perovskite Ceramics. *J. Am. Ceram. Soc.*, 96:3176-3182 <https://doi.org/10.1111/jace.12495>
- Wang, Z., Yu, L., Fan, S., and Tan, X. (2013). Giant dielectric permittivity in Li and Nb doped NiO. *Advanced Science Letters*, 19(6):1763-1765. <https://doi.org/10.1166/asl.2013.4522>
- Wei, X., Jie, W., Yang, Z., Zheng, F., Zeng, H., Liue, Y., and Hao, J. (2015). Colossal permittivity properties of Zn, Nb co-doped TiO₂ with different phase structures. *Journal of Materials Chemistry C*, 3(42):11005-11010. <https://doi.org/10.1039/C5TC02578H>
- Wu, J., Nan, C.-W., Lin, Y., and Deng, Y. (2002). Giant dielectric permittivity observed in Li and Ti doped NiO, *Physical Review Letters*, 89(21):217601. <https://doi.org/10.1103/PhysRevLett.89.217601>
- Yao, Z., Song, Z., Hao, H., Yu, Z., Cao, M., Zhang, S., Lanagan, M.T., and Liu, H. (2017). Homogeneous/inhomogeneous-structured dielectrics and their energy-storage performances. *Advanced Materials*, 29(20):1601727. <https://doi.org/10.1002/adma.201601727>