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Dielectric Characterisation of Borosilicate Glass for Microwave Substrate Application

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ABSTRACT

This work aimed to extract and characterize dielectric glass powder from borosilicate glass waste for microwave substrate application. The glass powder was obtained from the glass waste using ball-milling technique and particle size of 106 µm, 90 µm, 63 µm, 45 µm, and 25 µm were prepared through the sieving method. The glass powder was then characterized for its structural and dielectric properties using X-ray diffraction method (XRD) and open-ended coaxial probe (OECP) measurement technique, respectively. The OECP measurement probe was connected to an Agilent vector network analyser for the dielectric characterization in the 1 GHz to 12 GHz frequency range. XRD patterns indicated the phase formation and purity of the borosilicate glass powder. In addition, the dielectric properties of the powder exhibited an increasing trend with particle size reduction and a decreasing pattern with frequency. At 1 GHz, the relative permittivity (ε') of the powder was 3.27, 3.28, 3.29, 3.31, and 3.33 which reduced to 3.25, 3.26, 3.27, 3.29, 3.29 at 12 GHz for 106 µm, 90 µm, 63 µm, 45 µm, and 25 µm particle size, respectively. Similarly, the loss tangent (tanδ) of the powder varied from 0.0034, 0.0038, 0.0041, 0.0045, and 0.0047 to 0.0029, 0.0033, 0.0038, 0.0039, and 0.0042 in the same frequency for 106 µm, 90 µm, 63 µm, 45 µm, and 25 µm particle size, respectively. Thus, the powder exhibited low dielectric properties suitable for microwave substrate application.

INTRODUCTION

Commercial fiberglass and ceramic are the most commonly used fillers to produce PTFE-based microwave substrates due to their good electrical, thermal, and mechanical properties [1,2]. However, the increased demand for high-speed and low-cost microwave substrates demands alternative lower-cost filler materials to sustain the industry's advancement and reduce the cost of microwave substrates for consumers. Inorganic fillers such as borosilicate glass waste can be employed in this regard. The glass is of technological importance and has found applications in areas, such as toxic and nuclear waste immobilization, high-performance optics, and pharmaceutical primary packaging [3–5]. Also, recycling the glass could reduce the cost of inorganic fillers for microwave substrates and further eliminate environmental pollution without compromising performance, thereby turning waste into wealth [6,7]. In addition, the glass has comparable dielectric and mechanical properties to the commercial fillers [8–11]. Moreover, the glass possesses better rigidity and lower CTE. Although the glass is used in low-temperature cofired ceramic [12], its detailed dielectric properties and usage at microwave frequencies have not been reported. Hence, the glass needs to be characterized at high frequencies to determine its suitability for microwave substrate application.

EXPERIMENTAL DETAILS

The borosilicate glass waste obtained from Top Glove Sdn. Bhd. Selangor, Malaysia was sponged with water and dried at room temperature for a day to remove dirt. After that, the bottle was crushed and ground before using a plunger to further grind the crushed bottle into a powdery state and weighed via an AY 220 Shimadzu analytical balance with an accuracy of ±0.1 mg (Shimadzu, Kyoto, Japan). The powder was then milled (U.S. Stoneware, East Palestine, OH, USA) for a day at 45 rpm with a ball-to-milling ratio fixed at 20:1 to obtain a finer powder. The milling balls' diameter was 20 mm with a mass of 12.4 g. Thereafter, respective powder size of 106 µm, 90 µm, 63 µm, 45 µm, and 25 µm were obtained using laboratory test sieves (Endecotts Ltd. London, England). The XRD characterization of the glass powder was conducted using an X'pert Philips system (Model PW3040/60 MPD), while the dielectric characterization was conducted at 1 GHz to 12 GHz frequency range using an OECP technique connected to a vector network analyser (Agilent Technologies, Santa Clara, CA, USA).

RESULTS AND DISCUSSION

The representative XRD pattern of a 63 µm borosilicate powder is illustrated in Figure 1. The pattern exhibits a broad peak at $2\theta = 15° - 30°$ as reported in the literature [13]. However, no unwanted peak or shift is observed, confirming the purity of the glass.

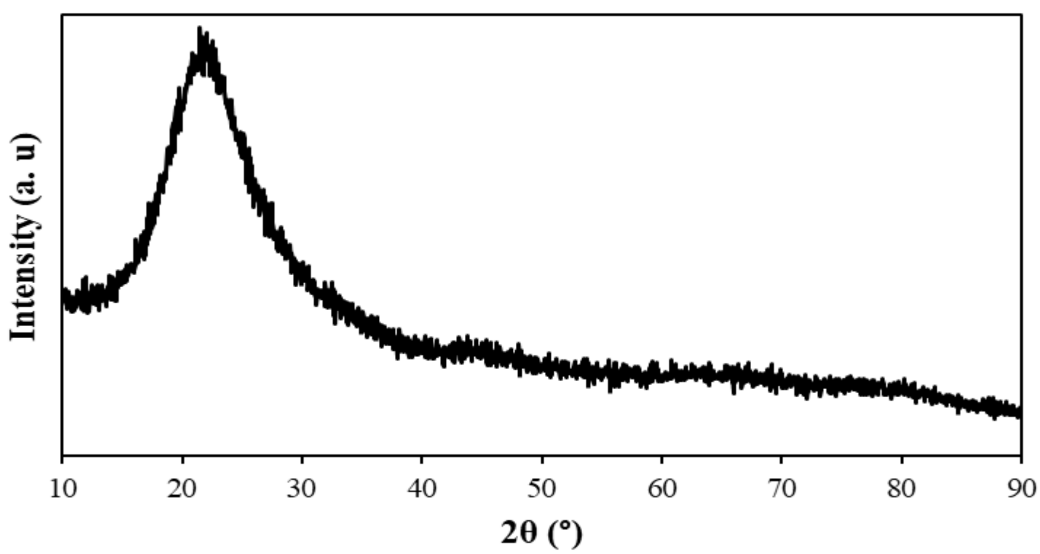

Figure 1. XRD pattern of borosilicate glass waste

The change in relative permittivity (ε') and loss tangent (tanδ) of the borosilicate glass powder with respect to frequency and particle size is illustrated in Figures 2 and 3. It can be seen that both ε' and $tan\delta$ decreased with frequency; a feature attributed to the fact that the hopping between Si+ and O- cannot keep up with the alternating applied electric field due to the presence of some lattice defects and oxygen vacancies [14]. At 1 GHz, the ε' and $tan\delta$ had respective values of 3.27, 3.28, 3.29, 3.31, 3.33 and 0.0029, 0.0033, 0.0038, 0.0039, 0.0042 for 106 µm, 90 µm, 63 µm, 45 µm, and 25 µm particle size. Similarly, the ε' and tanδ varied from 3.25 to 3.26, 3.27, 3.29, 3.29 and 0.0029 to 0.0033, 0.0038, 0.0039, 0.0042 at 12 GHz for the same particle sizes, respectively.

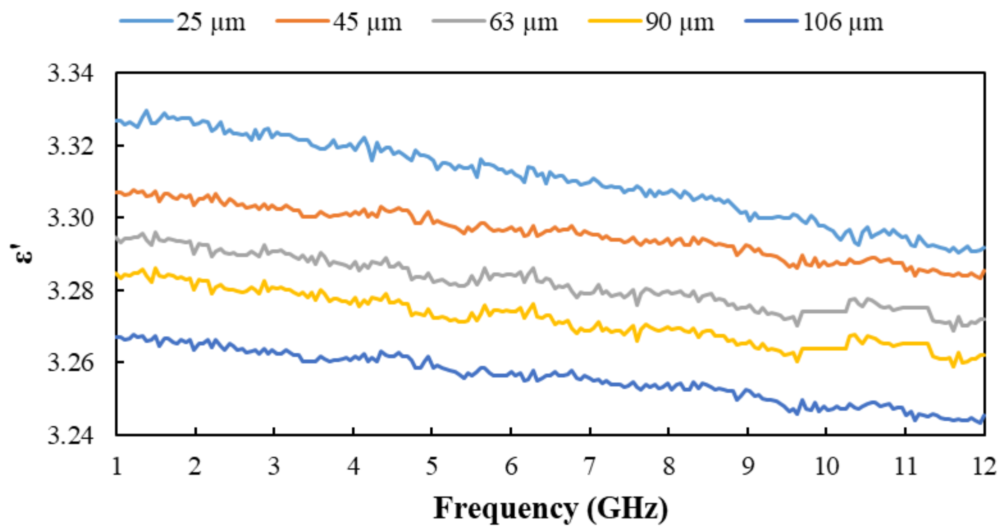

Figure 2. Variation of relative permittivity against frequency and particle size

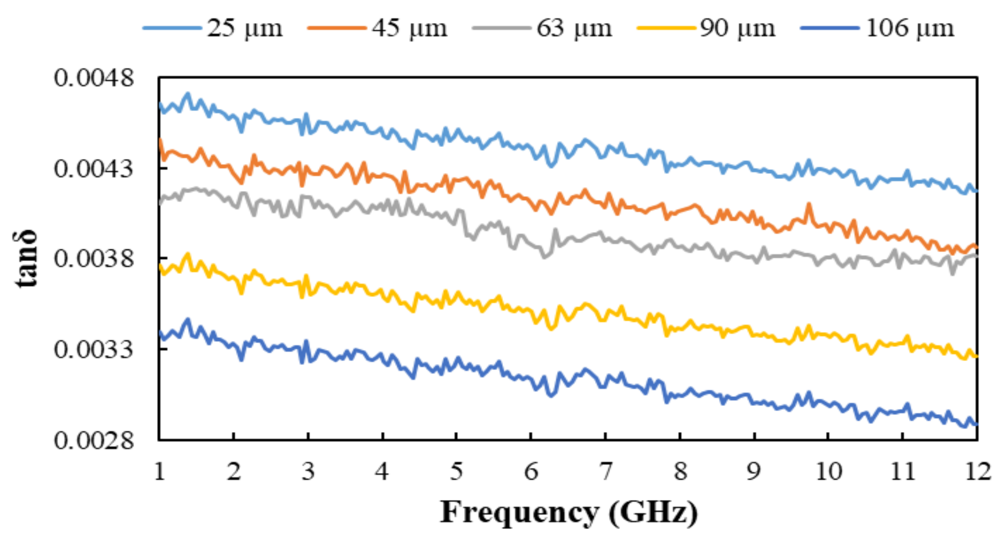

Figure 3. Variation of loss tangent against frequency and particle size

Figures 4 and 5 depict the variation of ε' and tanδ against particle size. It can be seen clearly that ε' and tanδ increased with particle size reduction. At 1 GHz, the powder has its ε' varied from 3.27 for 106 µm particle size to 3.28, 3.29, 3.31, and 3.33 for 90 µm, 63 µm, 45 µm, and 25 µm, particle size, respectively. A similar trend was observed at all selected frequencies. Also, at the same frequency of 1 GHz, the tanδ of borosilicate glass waste increased from 0.0034 for 106 µm to 0.0038, 0.0041,0.0045, and 0.0047 for 90 µm, 63 µm, 45 µm, and 25 µm particle size, respectively. This enhancement in the dielectric properties of the borosilicate powder is related to the increase in the surface area of the particles due to the reduction in particle grain size. Particles with larger surface areas tend to have good connectivity between one another and form a compact structure leading to an improved interfacial polarisation, thereby increasing the ε' and tanδ of the borosilicate powder [15–17].

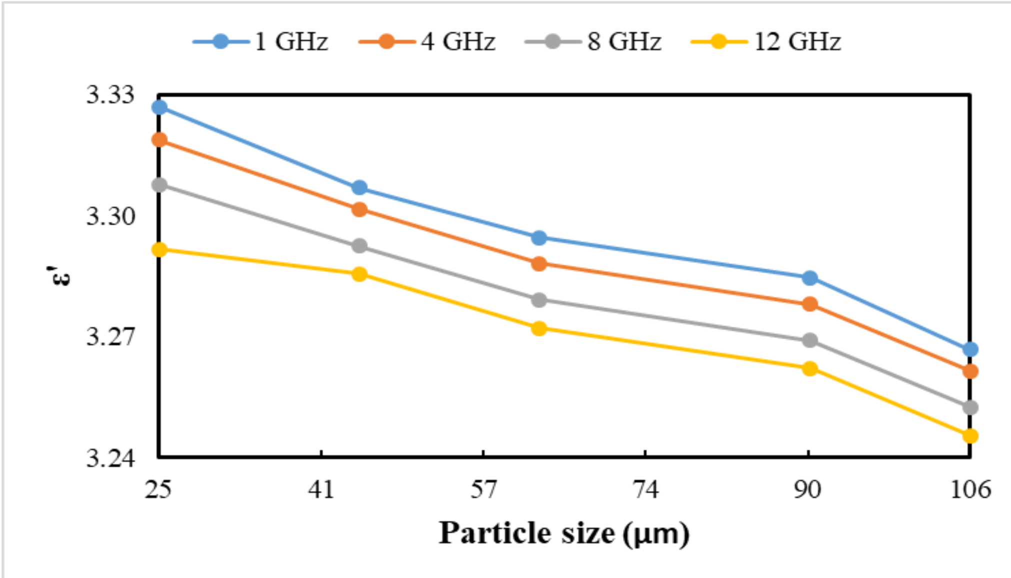

Figure 4. Variation of relative permittivity against particle size

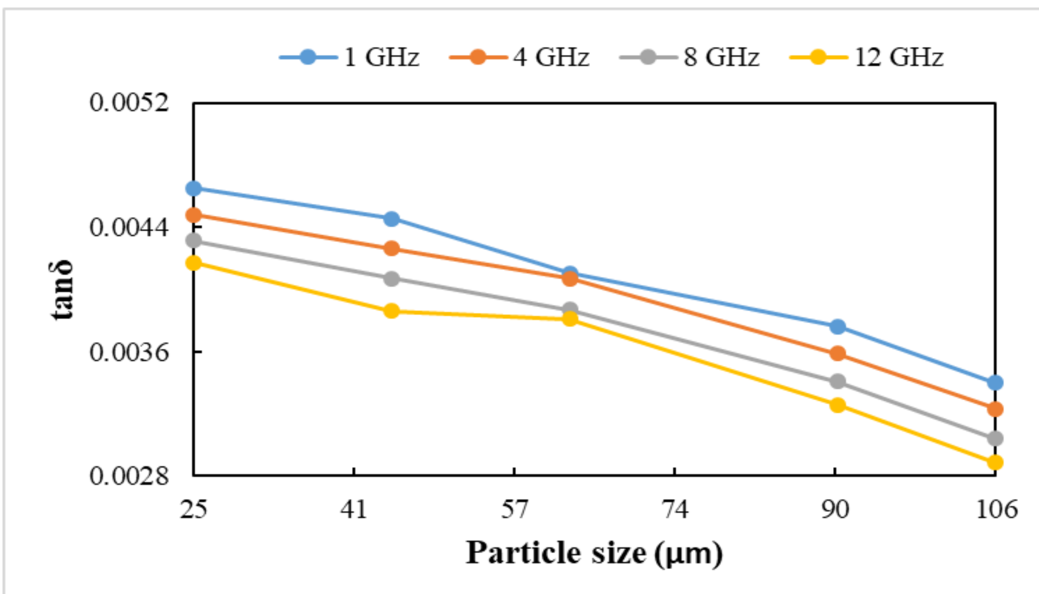

Figure 5. Variation of loss tangent against particle size

CONCLUSION

Borosilicate glass waste has been successfully recycled for use in microwave PTFE-based composites. The glass powder with different particle sizes was obtained through the ball milling technique. XRD diffractogram confirmed the phase and purity of the glass powder. In addition, the glass powder showed excellent dielectric properties at microwave frequencies, exhibiting mean ε' and tanδ values of 3.26 and 0.0031 for 106 µm borosilicate powder suitable for reinforcing PTFE matrix for microwave substrate application.

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