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Dielectric properties of magnesium oxide at microwave frequency

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ABSTRACT

To understand the role of a residual MgO phase plays inside a ceramic body, a simple magnesium oxide ceramics was prepared to investigate its microwave dielectric properties. The ε_r and τ_f values of specimens using simple MgO only vary in a small range at the investigated temperatures (1400–1550 °C) implying they are not sensitive to the sintering temperature. However, the $Q \times f$ is strongly related to the density of the ceramics and a high $Q \times f$ of ~113,600 GHz can be achieved by sintering the specimen at 1490 °C for 4 h. It indicates MgO may exist as a low-loss dielectric inside a dense ceramic body at microwave frequency.

1. Introduction

As the carrier frequency of interest in communication systems is being extended from GSM 900 MHz to ISM bands (2.4, 5.2 and 5.8 GHz) or even to millimeter wave range, some binary and ternary Mg-based oxides have received much more attention because of their high $Q \times f$ values which can retain a modest dielectric loss at high frequency regime [1] Compounds such as magnesium titanates and magnesium niobates are well known for having extremely low dielectric loss [2–6]. Modifications were also made to further lower the dielectric loss of these ceramics [7–11]. Cubic and rock-salt structured magnesium oxide (MgO), having a well known dielectric constant of 7–10, has found many applications as substrates, dc insulators, thin film buffer layers, dopants, catalyst and device supports etc. It is commonly found as a residual phase in the magnesium titanate or magnesium niobate ceramics due to a decomposition of compound or an over-compensated Mg [12–15]. Studies of the microwave loss of MgO in both polycrystalline and single crystal form have been performed experimentally as a function of temperature up to ~273 K [16–18]. However, the room temperature microwave dielectric properties of simple MgO itself have not been extensively studied. Consequently, the influence of an existing MgO phase on the microwave dielectric properties of the previously described compounds becomes ambiguous.

In the present study, the MgO ceramics was prepared by the conventional solid-state method to study its microwave dielectric properties. The resultant microwave dielectric properties were analyzed based upon the densification, the X-ray diffraction (XRD) patterns and the microstructures of the ceramics. The correlation between the microstructure and the $Q \times f$ value was also investigated.

2. Experimental procedure

Samples of the MgO ceramics were synthesized by the conventional solid-state method fusing high-purity (>99.5%) magnesium oxide powders (J.T. Baker, Japan). The starting material together with 5 wt% of a 10% solution of PVA as a binder (Polyvinyl alcohol 500, Showa, made in Japan) were granulated, forced through a 100-mesh sieve, and pressed into pellets with 11 mm in diameter and 5 mm in thickness. All samples were prepared by using an automatic uniaxial hydraulic press at 2000 kg/cm^2. These pellets were sintered at 1400–1550 °C for 4 h in air. The heating rate and the cooling rate were both set at 10 °C/min.

The crystalline phases of the sintered ceramics were identified by X-ray diffraction (XRD) using Cu Kα (λ = 0.15406 nm) radiation with a Siemens D5000

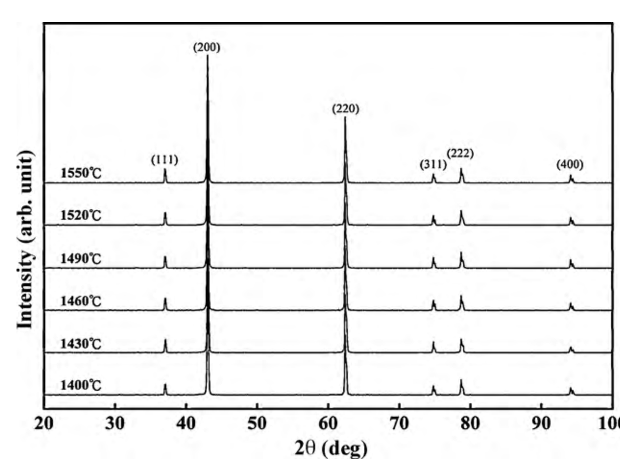

Fig. 1. X-ray diffraction patterns of MgO ceramics sintered at 1400–1550 °C for 4 h.

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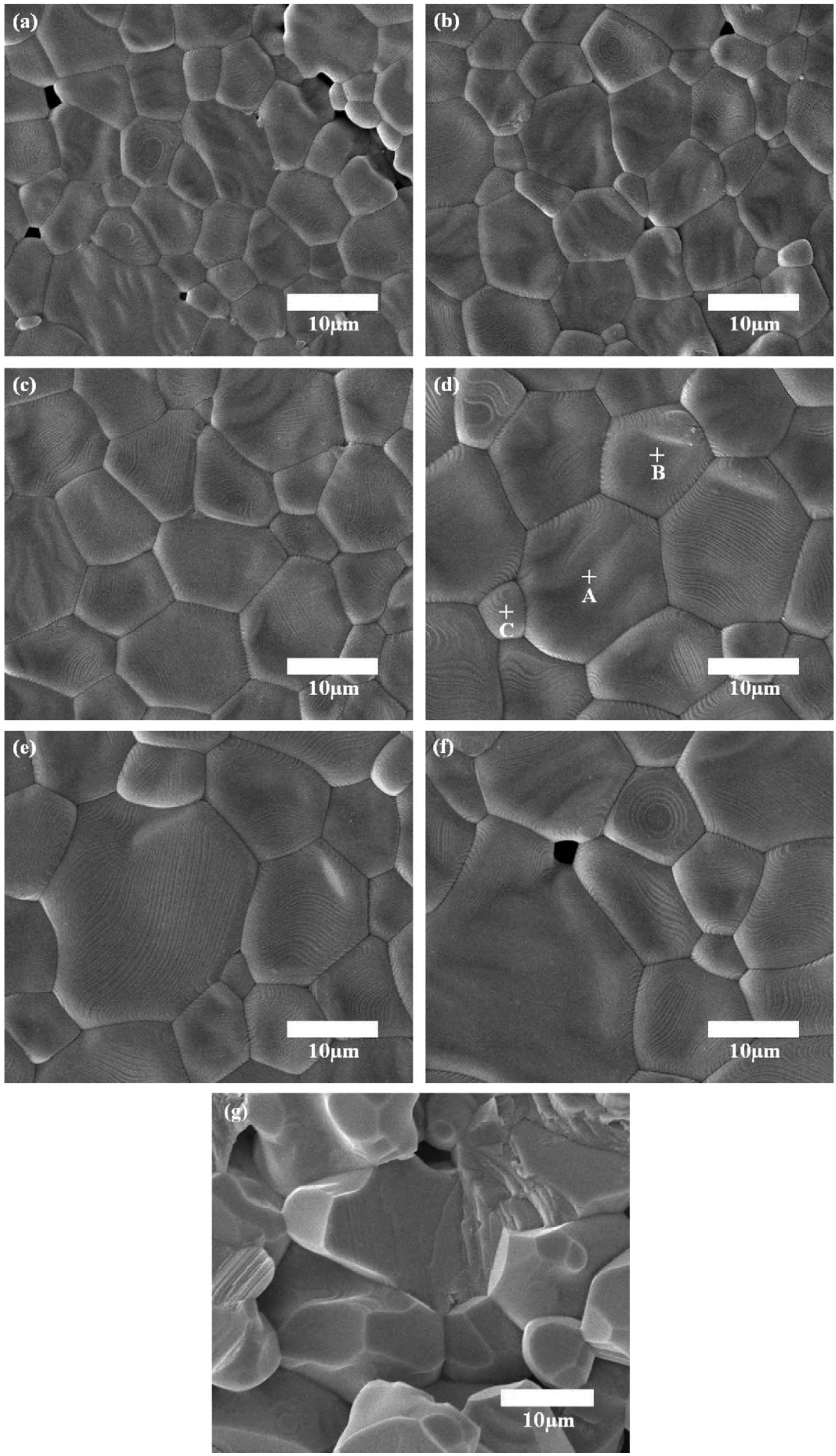

Fig. 2. SEM micrographs of MgO ceramics sintered at (a) 1400 °C, (b) 1430 °C, (c) 1460 °C, (d) 1490 °C, (e) 1520 °C and (f) 1550 °C for 4 h.

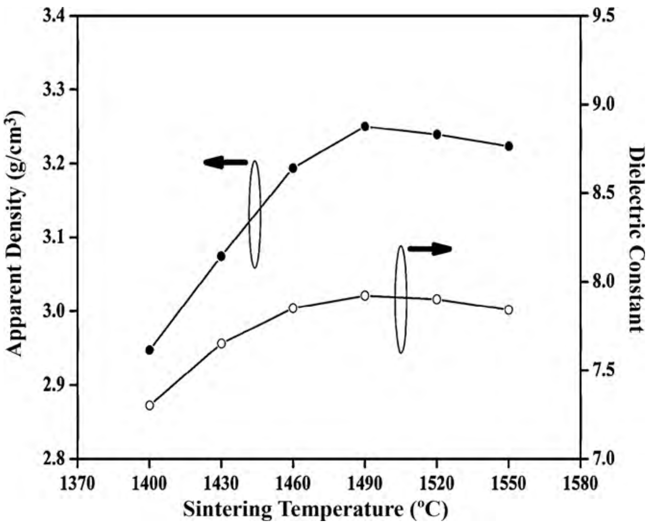

Fig. 3. Apparent density and dielectric constant of MgO ceramics as a function of its sintering temperature.

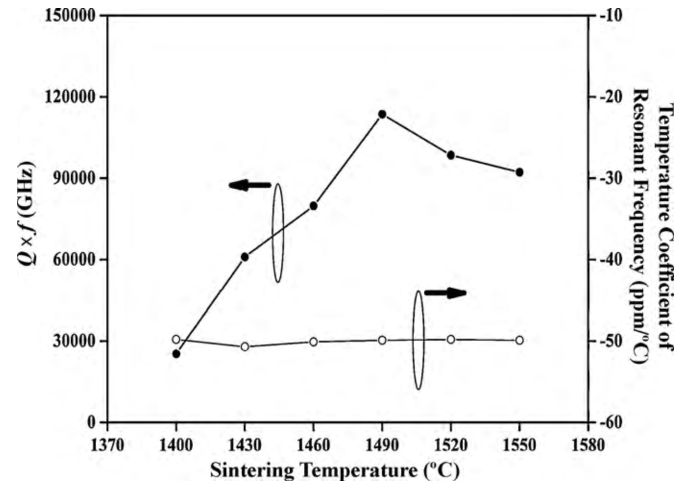

Fig. 4. $Q \times f$ (at 16.4 GHz) and τ_f values of MgO ceramics as a function of its sintering temperature.

diffractometer (Munich, Germany) operated at 40 kV and 40 mA. The microstructural observations and analysis of the sintered surfaces were performed by using a scanning electron microscope (SEM, Philips XL-40FEG, Eindhoven, the Netherlands) and an energy-dispersive X-ray spectrometer (EDS, Philips). The apparent densities of the sintered pellets were measured by the Archimedes method using distilled water as the liquid. The dielectric constants (ε_r) and the $Q \times f$ values at microwave frequencies were measured using the Hakki–Coleman dielectric resonator method [19,20]. A system combining a HP8757D network analyzer (Palo Alto, CA) and a HP8350B sweep oscillator (Palo Alto, CA) was employed in the measurement. An identical technique was applied to the measurement of the temperature coefficient of resonant frequency (τ_f). The test set was placed over a thermostat in the temperature range of 25–80 °C. The τ_f was calculated by noting the change in resonant frequency (Δf):

$$\tau_f = \frac{f_2 - f_1}{f_1(T_2 - T)} \quad (1)$$

where f_1 and f_2 represent the resonant frequencies at T_1 and T_2, respectively.

3. Results and discussion

Fig. 1 shows the room temperature X-ray diffraction (XRD) patterns recorded from the MgO ceramics prepared at different sintering temperatures (1400–1550 °C) for 4 h. A single MgO phase having a cubic and rock-salt structure with a measured lattice parameters of $a = b = c = 4.217$ Å was detected throughout the complete temperature range under test.

Fig. 2 illustrates the scanning electron microscopy (SEM) micrographs of the specimens using MgO at different sintering temperatures. The grain size of the specimens increased with increasing sintering temperature as expected. A well-developed grain morphology can be achieved by sintering specimens at temperatures 1460–1490 °C. However, an over-developed grain morphology is also observed at temperatures higher than 1490 °C leading to a presence of pores as shown in Fig. 2. In addition, few spotted close pores from the cross-section photo (Fig. 2g) may be a result from the vaporization of Pb because the initial MgO powder contains a max. 20 ppm of Pb. Typical EDS data of the MgO grains corresponding to certain spots as marked in Fig. 2d are illustrated in Table 1 and all the grains under test show a ratio Mg:O = 1:1 confirming the formation of a single magnesium oxide phase.

Table 1
The corresponding EDS data of the MgO grains from Fig. 2d.

Spots	Atom (%)	
	Mg K	O K
A	49.97	50.03
B	51.25	48.75
C	52.68	47.32

The apparent densities and dielectric constant of MgO ceramics at different sintering temperatures for 4 h are shown in Fig. 3. With increasing sintering temperature, the apparent density of specimen increases to a maximum value of 3.25 g/cm^3 at 1490 °C and thereafter it slightly decreases. The lowing in the density of the specimen is attributed to the appearance of pores as illustrated in Fig. 2. It suggests 1490 °C is a suitable temperature to achieve a well-sintered specimen. The variation of ε_r is consistent with that of density and a maximum ε_r of 7.92 can be obtained for MgO ceramics sintered at 1490 °C for 4 h. In addition, the dielectric constant only varies in a small range (7.31–7.92) at the investigated temperatures, implying it is not sensitive to the sintering temperature.

The $Q \times f$ and τ_f values of MgO ceramics sintered at different temperatures for 4 h are demonstrated in Fig. 4. By increasing the sintering temperature, the $Q \times f$ value being an important index for dielectric ceramic applications at microwave frequencies increases to a maximum value of 113,600 GHz (at 16.4 GHz) and decreases thereafter, which is mainly in response to the variation of density. Unlike previously recognized as a lossy media, it indicates the existence of MgO phase inside a dense ceramic body may be treated as a low loss region and a serious drop in the $Q \times f$ shall not be expected. The τ_f retains at the values around −50 ppm/ °C without significant variation as expected since there is no compositional change throughout the experiment.

4. Conclusion

The microwave dielectric properties of MgO ceramics have been studied in this paper. The ε_r and τ_f values of MgO ceramics are not sensitive to the sintering temperature and retain in 7.31–7.92 and around −50 ppm/ °C, respectively. However, the $Q \times f$ is strongly in response to the density of the ceramics and a high $Q \times f$ of ∼113,600 GHz can be achieved by sintering the specimen at 1490 °C for 4 h. It suggests the existence of MgO phase is not always a lossy media but may act as a low-loss dielectric inside a dense ceramic body.

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