Preparation and Properties of MCT Ceramics for RF and THz Applications

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Preparation and Properties of MCT Ceramics for RF and THz Applications

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***Abstract* — Dielectric ceramics of 0.95MgTiO$_3$–0.05CaTiO$_3$ were prepared via a solid-state reaction method. It is evident that high permittivity and low loss are correlated to high density and high purity in the THz frequency domain. Best dielectric properties were obtained for samples sintered at 1260 °C, which is attributable to their high density and high purity. However, the dielectric properties of the ceramics deteriorated when sintered above 1260 °C, which is attributed to the significantly increased content of second phase produced by 'over' sintering.**

***Index Terms* — Dielectric ceramics, THz application, resonators, filters.**

I. INTRODUCTION

In the past ten years, Terahertz (THz) technology has demonstrated extraordinary prospects due to its attractive applications in material, chemical, communication and life ciences [1–5]. Portable, low loss and light weighted THz devices are developed, for example sensors [6], resonators [7] and filters [8], to accelerate applications of THz technologies. However, the lack of advanced materials in the THz band is a major limited factor. Although obvious progress has been achived in the reliable measurement systems to test dielectric properties of materials in the THz band [9,10], systematic study on the materials with suitble dielectric properties was rarely reported. MgTiO$_3$, chemically a rhombohedral structure with space group R3c [11], is a popular microwave material which displays a relatively low permittivity (ε_r=17), high quality factor (Qf=160,000 at 7GHz) and negative temperature coefficient of resonant frequency (τ_f=50 ppm/ °C) [12]. Beside a high permittivity and quality factor, a near-zero temperature coefficient of resonant frequency is also demanded for commercial applications. It is found that with a small addition of 5mol% CaTiO$_3$ (orthorhombic structure with space group Pbnm) to the samples produces improved permittivity (21), quality factor (Qf=56,000 at 7GHz) and near zero τ_f [12]. It is reported that MgTiO$_3$ and CaTiO$_3$ do not react into solid solutions but separate phases due to the different crystal structures [13]. In this paper, 0.95MgTiO$_3$–0.05CaTiO$_3$ ceramics, i.e., MCT, were prepared under different sintering conditions. The effects of density, phase purity and microstructure on the dielectric properties of the samples were investigated in the THz spectral domain.

II. EXPERIMENTAL PROCEDURES

Ceramics of 0.95MgTiO$_3$–0.05CaTiO$_3$ were prepared via a conventional solid-state reaction route, with chemical reagents of MgO (CP, 99%), CaCO$_3$ (CP, 99%) and TiO$_2$ (CP, 99%). The reagents were firstly weighed based on the stoichiometry of 0.95MgTiO$_3$– 0.05CaTiO$_3$. The mixed powder was then calcined at 1150 °C for 2h with 1wt% of ZnO added as a sintering aid. Green bodies were pressed and sintered at different temperatures, 1240 °C, 1260 °C, 1280 °C and 1300 °C for 3h in air, respectively.

The crystal structures of the samples were identified with X-ray diffraction (XRD) using CuK$_\alpha$ radiation (X'pert PRO, Panalytical, Holand). The microstructure of the specimens was observed by a scanning electron microscope (SEM, TM-3000, Hitachi, Japan). Element analysis was carried out with Energy-Dispersive X-ray spectroscopy (EDX, Oxford instrument). Densities were obtained using the Archimedes' method. Microwave dielectric properties of the ceramics, including ε_r, Qf and τ_f, were measured with the parallel plate resonator method connected with a vector network analyzer (VNA) at 8.2GHz. The THz dielectric behavior of the samples between 0.22THz and 0.32THz were measured using a VNA2-driven quasi-optical transmission meter [14].

III. RESULTS AND DISCUSSION

The density of ceramics sintered at 1240 °C, 1260 °C, 1280 °C and 1300 °C were determined to be 3.778g/cm^3, 3.790g/cm^3, 3.790g/cm^3 and 3.790g/cm^3, respectively. The apparent density increased with increasing sintering temperature and a near constant density was achieved for samples sintered above 1260 °C. The XRD patterns of dense ceramics sintered at 1260 °C, 1280 °C and 1300 °C are shown in Fig. 1. The samples are multi-phase, with a main crystal phase of MgTiO$_3$ (JCPDS#79-0831), and minor ones of CaTiO$_3$ (JCPDS#22-0153) and MgTi$_2$O$_5$ (JCPDS#76- 2673). In Fig. 1, MgTi$_2$O$_5$ is indexed in the XRD for 1300 °C, MgTiO$_3$ is indexed for 1280 °C and CaTiO$_3$ is indexed for 1260 °C. The formation of the impurity phase MgTi$_2$O$_5$ is possibly resulted from the decomposition of $MgTiO_3$ [15]. With increasing sintering temperature, MgO maybe partially dissolved in the near region of grain boundary [15]. Therefore, the XRD peak intensity of $MgTi_2O_5$ increased with increasing sintering temperature. It is reported that $MgTi_2O_5$ could not be fully eliminated when ceramics were prepared using conventional sintering [16]. Here, the amount of ZnO and MgO is too small to be detected by XRD.

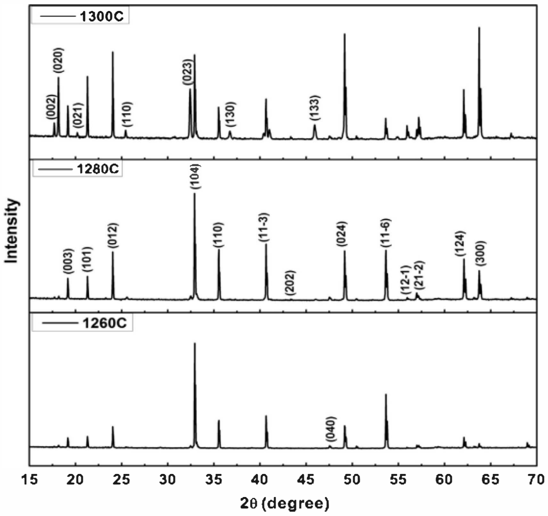

Fig. 1 XRD patterns of ceramics sintered at 1260 °C, 1280 °C and 1300 °C for 3h. Here, $MgTi_2O_5$ is indexed for 1300 °C, $MgTiO_3$ is for 1280 °C, and $CaTiO_3$ is only for 1260 °C.

Three different shapes of grains were observed in the ceramics sintered from 1260 °C to 1300 °C for 3h. An SEM image in addition to EDX analysis, of the ceramic sintered at 1280 °C is demonstrated in Fig. 2. According to the semi-quantitative molar ratio of Mg/Ti and Ca/Ti, the big block-shaped grains(1) were identified as $MgTiO_3$ due to a Mg/Ti ratio (0.97) of about 1:1. The small square block- shape grains(2) were identified as $CaTiO_3$ due to a Ca/Ti ratio (0.96) of about 1:1. Moreover, the small bar-shaped grains(3) were identified as a $MgTi_2O_5$ due to Mg/Ti ratio (0.52) of about 1:2.

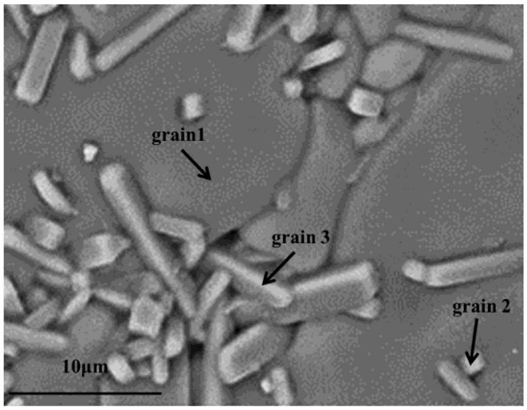

Fig. 2 SEM image of ceramic sintered at 1280 °C for 3h.

The microwave dielectric properties at 8.2GHz for ceramics sintered at different temperatures are revealed in Fig. 3. The improvement of microwave dielectric properties for samples sintered from 1240 °C to 1260 °C for 3h is attributed to the increase of the density. The maximum value of Qf=91,238GHz (at 8.2GHz) and ε_r=20.5 were obtained for the ceramic sintered at 1260 °C. The grain size increases with increasing sintering temperature so that the total area of the grain boundary is reduced, leading to an increase of the quality factor. However, the permittivity and Qf for samples sintered above 1260 °C both decreased. The reason for this is probably due to the increasing second phase content, as identified by XRD and SEM analysis, rather than agrain size effect in the dense samples. The sample sintered at 1240 °C was eliminated from the THz investigation because of its low density and low permittivity. According to the algorithm in the work of Yang et al. [9], dielectric properties (permittivity and loss tangent) can be obtained through complex transmission spectra of ceramics measured over abroad band frequency domain, i.e. 0.22THz to 0.32THz. The permittivity of ceramics sintered at 1260 °C, 1280 °C and 1300 °C for 3h were around 18, exhibiting minimal dispersion. The dielectric losses of the samples varied significantly from 0.0019 (sintered at 1260 °C) to 0.0072 (sintered at 1300 °C) at 0.22THz as displayed in Fig. 4. This indicates that the $MgTi_2O_5$ second phase had a obvious influence on the increase of loss not only in the microwave frequency domain [17] but also in the THz frequency domain (Fig. 4).

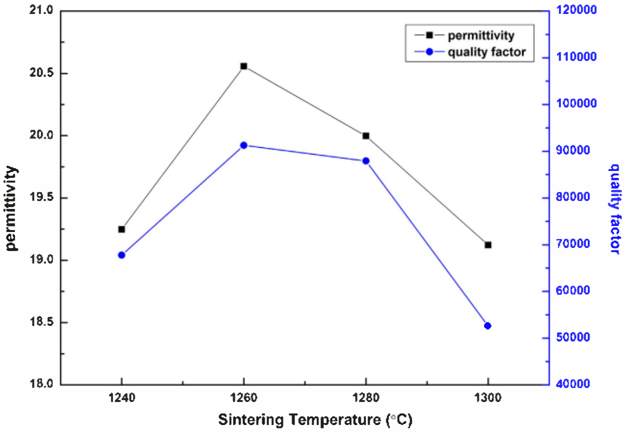

Fig. 3 Dielectric properties at 8.2GHz of ceramics sintered at 1240 °C, 1260 °C, 1280 °C and 1300 °C for 3h.

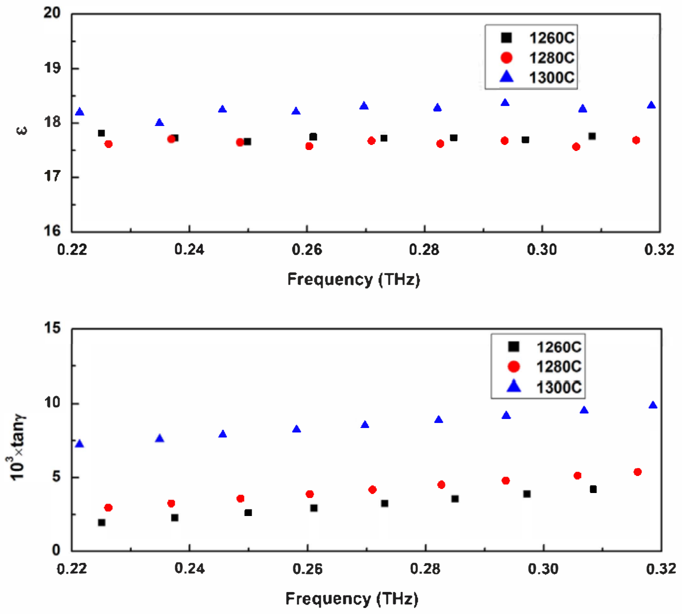

Fig. 4 Calculated permittivity (top) and loss tangent (bottom) of ceramics sintered at 1260 ˚C, 1280 ˚C and 1300 ˚C for 3h in the frequency range 0.22THz to 0.32THz.

IV. CONCLUSION

Dielectric ceramics of 0.95MgTiO$_3$–0.05CaTiO$_3$ were prepared via a solid-state reaction method. Best dielectric properties were achived for samples sintered at 1260 ˚C for 3h, which is attributable to their high density and high purity. However, the dielectric properties of the samples deteriorated when sintered above 1260 ˚C. This is attributed to the significantly increased content of second phase due to 'over' sintering of samples. It is evident that high permittivity and low loss are correlated to high density and high purity in the THz frequency domain.

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