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Characterization of dielectric properties of oxide materials in frequency range from GHz to THz

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Abstract

We measured complex dielectric permittivity using THz time-domain spectroscopy (THz-TDS) to clarify the dielectric properties of oxide materials in a frequency range from GHz to THz. Piezoelectric and ferromagnetic oxide single crystals, such as quartz (SiO_2), zinc oxide (ZnO), Bi substituted rear-earth iron garnet (BiRIG), and $LiTaO_3$ (LT), were used. We obtained the complex dielectric permittivity of these materials in a frequency range from 100 GHz to 2 THz. The ε' and ε'' obtained for SiO_2 were in agreement with previous reports. We observed dielectric relaxation in ZnO crystal from 100 GHz to 1 THz, which originated from n-type conductivity. In the BiRIG, the values of the dielectric permittivity increased as the frequency increased, and the values of the dielectric permittivity with the magnetic field were smaller than those without the magnetic field throughout the measured frequency range. In a comparison between congruent $LiTaO_3$ (CLT) and stoichiometric $LiTaO_3$ (SLT), the ε_{33} of the CLT was very similar to that of the SLT, but a lot of difference was between the ε_{11} of evident CLT and SLT within the measured frequency region. We determined that the point defects had profound effect on the dielectric performance of the LT.

Keywords: THz-TDS; Dielectric properties; ZnO

1. Introduction

The frequency range from 800 MHz to 2 GHz has been used in developing wireless communication technology so far. New telecommunication systems in the planning stage, such as an intelligent traffic system (ITS), will use a higher range (from 30 to 300 GHz and over). Moreover, ubiquitous communication networks will be built in the near future using the frequency in a range from GHz to THz. However, the THz wave should be employed for medical and security technology. Therefore, clarifying the dielectric properties for electrical devices with regard to the frequency range from GHz to THz is important.

Coherent THz radiation has been obtained as a further development in the femtosecond pulse laser (fs laser), and thus, THz time-domain spectroscopy (THz-TDS) enables characterizing the dielectric properties ranging from GHz to THz. This method has the advantages of principle and convenience for measuring the complex dielectric permittivity in this frequency range in comparison with other methods, such as far-infrared Fourier transform spectroscopy and the Hacky–Coleman method.[1–3]

In this paper, we report THz-TDS measurements of piezoelectric and ferromagnetic oxide single crystals to clarify material performance and the complex dielectric permittivity within the range of the GHz and THz wave (from 100 GHz to 2 THz).

2. Experimental

We prepared Z-plate quartz (Z-SiO_2), Z-plate zinc oxide (Z-ZnO), (1 1 1) Bi substituted rear-earth iron garnet (BiRIG), Y-plate congruent $LiTaO_3$ (Y-CLT), and Y-plate stoichiometric $LiTaO_3$ (Y-SLT) for measurement samples. The Z-SiO_2 and Z-ZnO were grown by the hydrothermal growth method.[4] The BiRIG (the material for an optical isolator made by the Mitsubishi Gas Chemical Company Inc. in Japan) was grown by the liquid phase epitaxy method. The Y-CLT was grown by the conventional Czochralski method, and the Y-SLT was grown by double-crucible Czochralski method.[5]

We used a THz-TDS apparatus (Jspec-2001 made by the Mutsumi Corporation in Japan) with a femtosecond Ti-sapphire plus laser (MaiTai made by the Spectra Physics Corporation in the USA).[3] Fig. 1 shows a schematic illustration of the optical configuration in the apparatus. After the light of the fs laser is divided into two optical paths by a beam splitter, one is guided to an emitter, and the other is guided to a detector, respectively. Both

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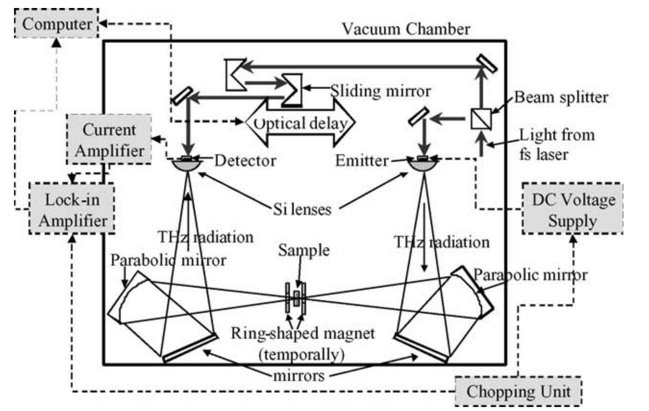

Fig. 1. Schematic illustration of optical configuration in THz-TDS apparatus. The bold arrows indicate the fs laser light, and the broken lines show the electrical flow. The ring-shaped permanent magnets were attached when BiRIG was measured.

Table 1
Experimental conditions

Sample	Thickness (mm)	Aperture (mm in diameter)
Z-SiO_2	0.407	8
Z-ZnO	0.516	8
(1 1 1) BiRIG	0.236	8
Y-CLT	0.264	5
Y-SLT	0.732	5

the emitter and detector consisted of a photoconductive antenna made of low-temperature grown GaAs. The THz electromagnetic waves radiate from the emitter antenna. The measuring frequency ranges from 60 GHz to 2.8 THz, and the frequency resolution is 2 GHz. This apparatus was configured to transmit THz radiation through the samples.

The experimental conditions are listed in Table 1. The optical aperture was 5 mm or 8 mm in diameter, and we measured the materials at room temperature. We measured ε_{11} in Z-SiO_2 and Z-ZnO and ε_{11} and ε_{33} in Y-CLT and Y-SLT. In the BiRIG, we measured the dielectric permittivity with and without an applied external magnetic field. A pair of ring-shaped permanent magnets was temporally arranged along the THz radiative direction, as shown in Fig. 1. The direction of the magnetic field was parallel to the ⟨1 1 1⟩ direction in the BiRIG, and the magnitude of the field was 190 mT.

3. Results and discussions

Fig. 2 shows the results of the complex dielectric permittivity (ε'_{11} and ε''_{11}) of the Z-SiO_2 in the range from 80 GHz to 1.8 THz. The ε'_{11} was 4.45 for the measuring frequency, and the ε''_{11} was about 0.03. The ε'^{T}_{11} at 1 KHz was 4.52, so the dielectric permittivity of quartz was uniform in the range from KHz to THz. These results were consistent with a previous report.[6]

The results of the dielectric permittivity for Z-ZnO crystal are shown in Fig. 3. The ε'_{11} was 7.9 and was constantly within the measuring frequency range. The ε'^{T}_{11} at 1 KHz was 8.4 and this value was slightly bigger than the measuring values. However,

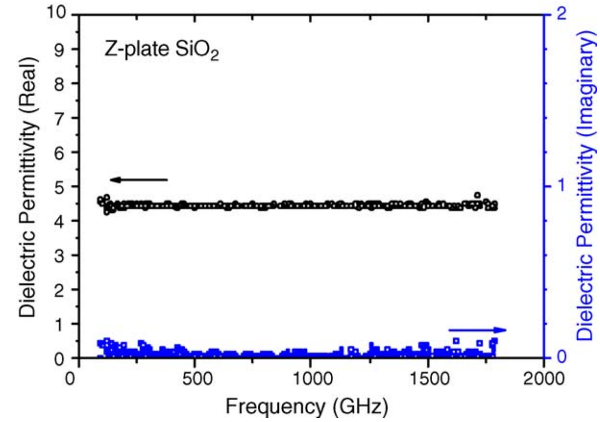

Fig. 2. Real (ε'_{11}) and imaginary (ε''_{11}) parts of complex dielectric permittivity of Z-SiO_2. The open circles indicate ε'_{11} and the open squares indicate ε''_{11}.

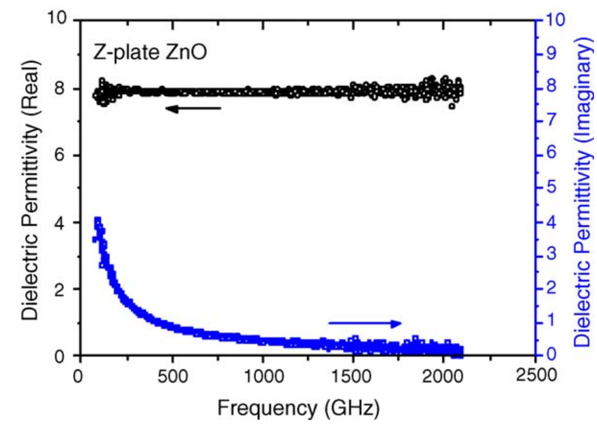

Fig. 3. Real (ε'_{11}) and imaginary (ε''_{11}) parts of complex dielectric permittivity of Z-ZnO. The open circles indicate ε'_{11} and the open squares indicate ε''_{11}.

the ε''_{11} decreased as the frequency increased. Also, the dielectric relaxation from 100 GHz to 1 THz was observed. This shows Drude effect, which is in ZnO crystal of n-type conductivity.

The results of the (1 1 1) BiRIG with and without the external magnetic field are shown in Figs. 4 and 5, respectively. The BiRIG is ferromagnetic crystal, and the magnetism axis is along

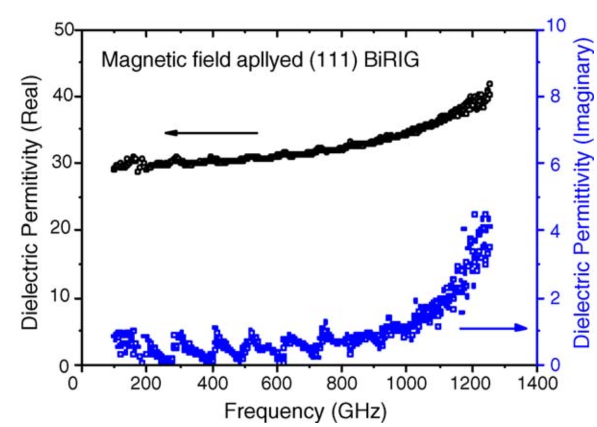

Fig. 4. Real and imaginary parts of complex dielectric permittivity of (1 1 1) BiRIG with external magnetic field. The open circles indicate the real part, and the open squares indicate the imaginary part.