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Dielectric measurement using non-contact microwave single probe for dielectric materials

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Abstract A high frequency dielectric measurement method was proposed using a non-contact probe. The microwave reflection intensity was measured for Al_2O_3 and $SrTiO_3$ substrates at room temperature as a function of distance between sample and probe. The difference of reflection intensity for Al_2O_3 and $SrTiO_3$ substrates was observed in the region where the distance of 0.2 mm between sample and probe, and it was caused from dielectric permittivities of samples. The reflection coefficient of sample was estimated in comparison with results of electromagnetic simulation. The reflection intensity for Al_2O_3 and $SrTiO_3$ substrates was transformed to dielectric permittivity at reflection intensity minimum point.

Keywords Microwave · Non-contact probe · Reflection intensity · Dielectric materials

1 Introduction

The resonance method is widely used for high frequency measurement of dielectric materials [1, 2]. Although the resonance method shows the accurate data for dielectric materials, the measurement frequency is limited by the resonator size. The impedance (Z) method on the other hand measures the continuous dielectric spectrum in frequency domain. Commonly, in the dielectric measurement, the electrodes are deposited on the surface of sample in order to load the voltage. Hence the obtained data present total dipole moment behaviors of sample between both electrodes. The dielectric and ferroelectric materials have however uneven dipole moment behaviors that form the domain structure [3], and domain structure should be investigated in microwave region. However, general dielectric measurement techniques are difficult for investigating the local dielectric properties at high frequency region. Therefore a high frequency measurement method for the local dielectric properties should be developed.

Identically, a high frequency measurement method for the local dielectric properties is desired as follows below, (i) measurable the local dielectric property, (ii) prevent resonance phenomena, and (iii) wide frequency range.

Recently, near field scanning microwave microscopy was developed by Steinhauer et al. using a $\lambda/4$ coaxial resonator and contact probe, and local dielectric properties are investigated with a contact probe scanning for the surface of sample at 7.2 GHz [4, 5]. To the contrary, the free space method is a famous non-contact measurement method for the dielectric material using a horn antenna [6]. However, the dielectric lens in free space method is difficult to focus the electromagnetic (EM) wave generated by a horn antenna. Therefore the local dielectric properties at high frequency are difficult to be observed with a free space method.

In this study, a non-contact probe attached to coaxial cable was used in order to focus the EM wave. In order to measure the wide frequency region and observe local dielectric properties, the microwave reflection (r) intensity is measured using a non-contact probe. The non-contact probe is useful for preventing resonant phenomena at high frequency, however the impedance (Z) of sample was changed as a function of phase (θ) in incidence electric (E) field to sample, in previous study [7]. The θ is denoted as $\theta = \beta l$, where β is $2\pi f/c$ and l is electric length for transmission line. If θ of incidence EM wave to sample is adjusted to $n\pi/2$, where n is integer, Z presents sample's one. The EM wave was transmitted to

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sample. However Z of sample at $\theta \neq n\pi/2$ is increasing and reflects the EM wave. Hence, it is important to measure r intensity with θ as $n\pi/2$ for estimating dielectric permittivity (ε_r) of sample.

In this report, we propose a dielectric measurement method for high frequency region. The r intensity using a non-contact probe was measured up to 9 GHz for dielectric material, and r intensity was successfully transformed to ε_r of sample.

2 Experimental

The measurement system was constructed from an oscillator generated by a Gunn diode, phase (θ) shifter (0–360°), directional coupler, detector (diode), coaxial cable (length: 73 mm) and probe (0.99 mmϕ, Micro Denshi Co. Ltd.). The frequency was ranged from 8.5 to 11 GHz. The probe was formed from semi-rigid coaxial cable. The probe was sized 8 mm for length. The *XYZ*-stage was moved by D.C.-servomotors (Chuo Precision Industrial Co. Ltd.), and they were controlled by a personal computer using GP-IB interface. The sample was selected for Cu-plate (reference, size: $40 \times 40 \times 2.0$ mm^3), Al_2O_3 (ALO) and $SrTiO_3$ (STO) substrates (Shinko-sha Co. Inc., size: $10 \times 10 \times 0.5$ mm^3). The reverse surface of ALO and STO substrates was coated by Au thick film using D.C.-sputtering method. The reflection (r) intensity was measured at room temperature as a function of distance (d) between probe and sample.

The electromagnetic (EM) analysis was carried out using finite differential time domain (FDTD) method using MAGNA/TDM software (CRC Solutions Corp.). The simulation model was surrounded with perfect multi-layer (PML) that absorbs perfectly EM wave. The size and physical quantities were input to the simulation model, and then a Gaussian pulse was loaded to simulation model. The reflection coefficient (Γ) and Z were calculated.

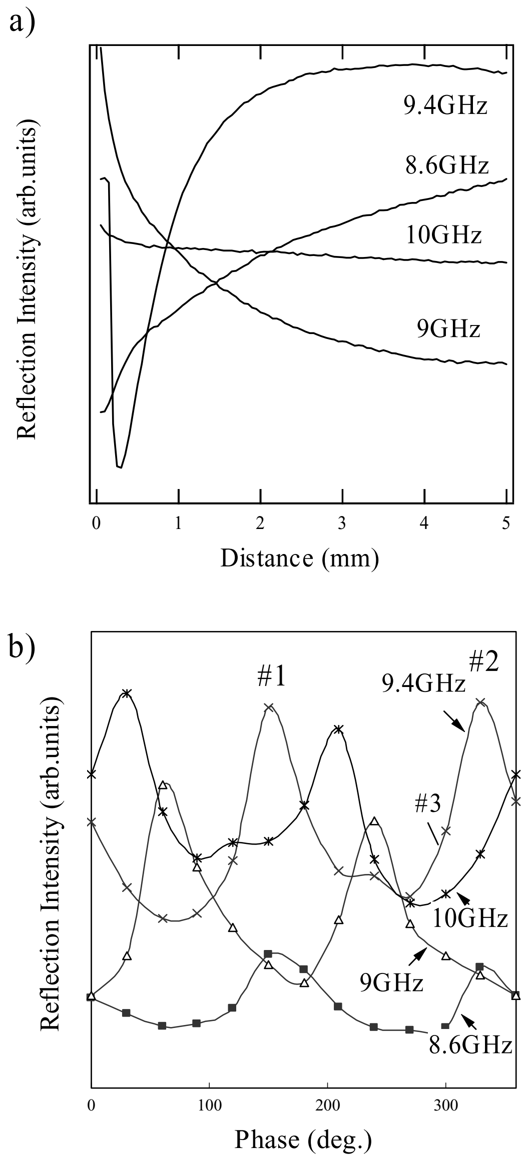

Fig. 1 Reflection intensity for Cu-plate as a function of distance between probe and Cu-plate (a), and reflection intensity for Cu-plate versus phase at distance of 0.2 mm (b) from 8.6 to 10 GHz

3 Results and discussion

3.1 Reflection intensity for Cu-plate and dielectric materials

Figure 1 shows the r intensity for Cu-plate as the function of distance (d) between probe and Cu-plate, and θ at measurement frequency (f) region. At first, r intensity was measured as a function of d, as shown in Fig. 1(a). The measurement was done without θ shifter. The r intensity showed the minimum values at $d = 0$ mm for 8.6 GHz and $d = 0.2$ mm for 9.4 GHz, and r intensity at other frequencies was increased with decreasing d in Fig. 1(a). From obtained r intensities at 8.6 GHz and 9.4 GHz in Fig. 1(a), we consider the factor about appearing r intensity minimum, i.e., the probe length, quarter wavelength ($\lambda/4$) of EM wave and θ at measurement f. Firstly, probe length and $\lambda/4$ of EM wave at measurement f were considered. Although the probe length is as same as $\lambda/4$ of EM wave at 9.4 GHz (8 mm), $\lambda/4$ of EM wave at 8.6 GHz is, to the contrary, 8.72 mm. Hence, the probe length is not related to the appearing of r intensity minimum. Secondary, in order to measure the θ at $d = 0.2$ mm at measurement f, θ shifter was equipped for measurement system. Figure 1(b) shows the r intensity versus θ at measurement f range. Although r intensity showed the different values because of oscillator's f dependence, r intensity was periodically changed with increasing θ. Therefore, the resonant

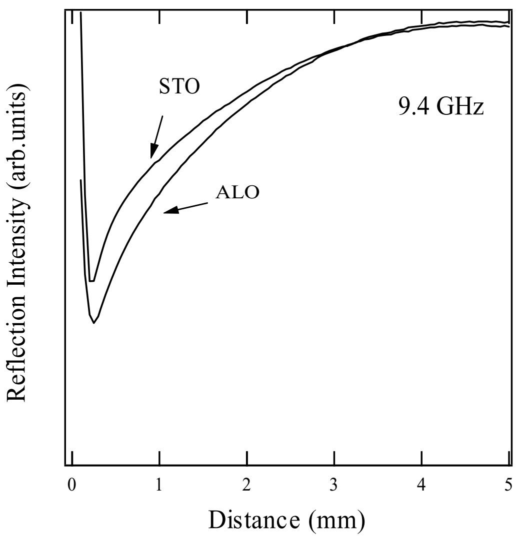

Fig. 2 Reflection intensity for Al_2O_3 and $SrTiO_3$. The minimum point of reflection intensity at 9.4 GHz was appeared at distance of 0.2 mm between probe and sample, and difference of reflection intensity of samples was clearly observed

phenomena in this measurement do not occur. The peaks of r intensity at 8.6 GHz and 9.4 GHz were found about 150° and 330° (#1, #2), and the curve shapes of them are accordance with periodically in Fig. 1(b). However, r intensity at 8.6 GHz is slightly shifted to lower θ. The minimum r intensity at 9.4 GHz in Fig. 1(a) was measured at $\theta = 240°$ (#3). If peak #1 in Fig. 2(b) is consider as $\theta = 0°$, peak #3 is $3\pi/2$.

Therefore the θ is the main factor of appearing r intensity minimum. The θ of EM wave incidence to sample at 8.6 GHz and 9.4 GHz is assumed to be $n\pi/2$ from Fig. 1(b). The r intensity at 9.4 GHz shows the minimum value at $d =$ 0.2 mm, however r intensity at 8.6 GHz appears the minimum value at $d = 0$ mm because of slight shifting of θ. Therefore, it is possible that r intensity minimum is appeared at other f with adjusting θ.

Figure 2 shows the r intensity for ALO and STO at 9.4 GHz as a function of d. The r intensity was increased with increasing ε_r of sample (ALO:$\varepsilon_r = 10$, STO:$\varepsilon_r = 310$). The EM wave was attained and reflected at reverse sides of sample, and reflected EM wave was then detected by the non-contact probe. In the Fig. 2, the positions of showing r intensity minimum values for ALO and STO did not shift, because optical lengths for ALO and STO, denoted as $(\varepsilon_r)^{0.5} \times$ (0.5 mm), were smaller than $\lambda/4$. Therefore θ at $d = 0.2$ mm in Fig. 2 is kept to $n\pi/2$. Therefore it is important for keeping the θ as $n\pi/2$ that EM wave is conducted to electrode (Cu-plate) or transmitted to dielectric materials (ALO, STO). Various frequencies dependence of dielectric materials may be measured with non-contact probe. In order to investigate r intensity property, the EM analysis was carried out using simulation model.

The time domain E-field distribution of ALO ($\varepsilon_r = 10$) was calculated by EM analysis. The E-field distribution to space behaves as a dipole antenna, and other part of E-filed distribution is irradiated to sample. The area (S) of E-field irradiated to sample was difficult to be calculated from EM analysis. However, from E-field distribution, Γ and Z were calculated by EM analysis software. The Γ is also presents minimum value at $d = 0.2$ mm, and Γ and Z are calculated to be 0.34 and 98.7Ω at $d = 0.2$ mm, respectively. The relationship between Γ and Z is expressed as follows,

$$\Gamma = (Z - Z_o)(Z + Z_o), \tag{1}$$

where Z_o is the characteristic Z defined as 50 Ω. The Γ and Z at $d =$ 0.2 mm are well accordance with above relationship [6].

3.2 Reflection intensity and reflection coefficient of ALO and STO

Figure 3 shows the r intensity and Γ properties of ALO. The solid line is experimental r intensity, and open circle is calculated value of EM analysis. At $d = 0.2$ mm, Γ of ALO is estimated to be 0.34. From results in Section 3.2, Z matching was found at $d = 0.2$ mm. In addition, Γ of STO is also estimated to be 0.36. The Γ of sample was successfully estimated in comparison between experimental and analysis data. The transformation from r intensity to Γ involves background-calibration, and it is solved in comparison with experimental value (r intensity) and EM analysis (Γ). In addition, the d at minimum r intensity can be considered as the l between probe and sample.

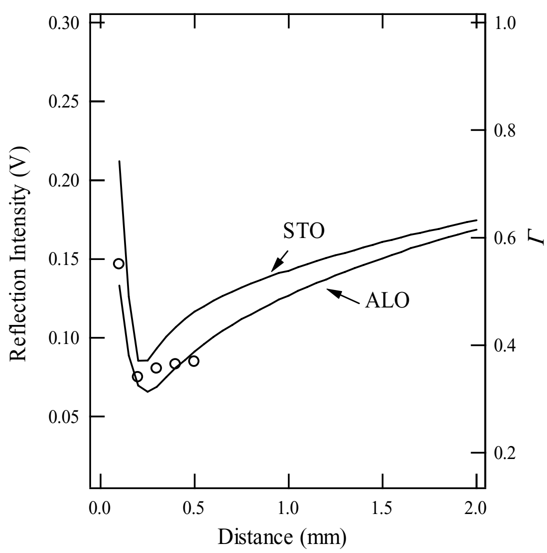

Fig. 3 Plots of reflection intensities (experimental: solid line) of Al_2O_3 and $SrTiO_3$ and coefficient (analysis: open circle) of Al_2O_3

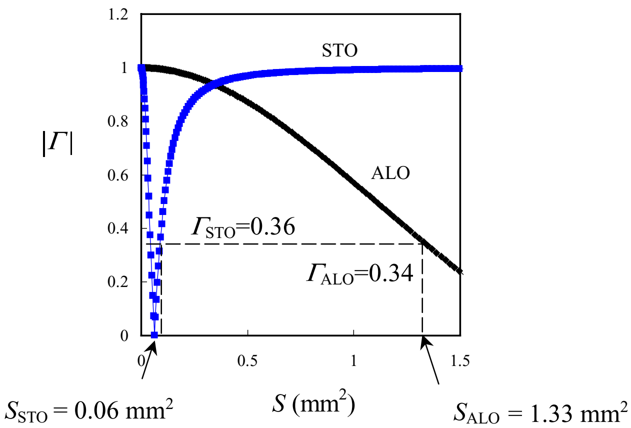

Fig. 4 Reflection coefficient versus effective area of transmitted electric field in samples (a), and dielectric permittivity versus effective area (b)

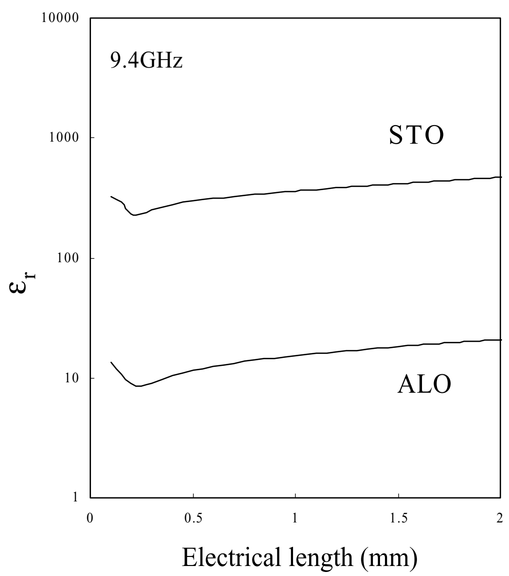

Fig. 5 Dielectric permittivity of samples versus electrical length

3.3 Transform to dielectric permittivity

From the result in Section 3.1, Z in Eq.(1) indicates Z of sample ($Z_l = 1/j\omega C$, where C is capacitance of sample). The C of sample is $C = \varepsilon_r \varepsilon_o S/(0.5\ \text{mm})$, where S is effective are of transmitted E-field in the sample.

Figure 4 shows the Γ as a function of S (a). The S was estimated to be 1.33 mm^2 (ALO) and 0.06 mm^2 (STO) in Fig. 4. As shown in Fig. 4, S was decreased with increasing ε_r. The transmitted E-field in sample is decreased with increasing ε_r, and r intensity became higher value, as shown in Fig. 2.

From above all discussions, the ε_r at $d = 0.2$ mm was estimated using Eq. (2), as follows

$$\varepsilon_r = 2\,|\,\Gamma|\ \sin\theta[\omega C_o\, Z_o(|\,\Gamma|^2 + 2|\,\Gamma|\cos\theta + 1)], \tag{2}$$

where $\theta = 90^\circ$, $\omega = 2\pi f$, $C_o = \varepsilon_o S/(0.5\ \text{mm})$ and $Z_o = 50\Omega$ [8]. Figure 5 shows the log plot of ε_r versus l at 9.4 GHz. The ε_r of ALO and STO is estimated to be 8.9 and 290. The ε_r in Fig. 5 is accordance with the ε_r of samples.

4 Conclusion

A high frequency dielectric measurement method is proposed using a non-contact probe. The reflection intensity measurement at high frequency was carried out for dielectric materials. The reflection intensity showed the minimum value in the region where the distance of 0.2 mm between sample and probe. The reflection intensity minimum point presented an impedance matching one. The dielectric permittivity of samples was calculated by using reflection intensity minimum point value and result of electromagnetic analysis.

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