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Ring Resonator Method for Evaluation of Dielectric Property of Thin Layers in Microwave Region

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The configuration of the ring resonator was first designed by high frequency electromagnetic field simulation. The ring resonator of Cu was formed on the sapphire substrate by a photolithography technique. A sample of dielectric thin layer was pressed on a ring resonator formed on a sapphire substrate. Dielectric permittivity was determined by fitting the resonance frequency observed with that simulated using the electromagnetic-field analysis, while the *Qf*-value of a sample was determined from the half bandwidth observed. Dielectric properties of some samples, such as a $SrTiO_3$ single crystal substrate, some ceramics thin plates and a ceramics/polymer composite thick film, could be determined accurately by this method, which indicated that the ring resonator method developed in this study would be a powerful tool to evaluate microwave dielectric properties of dielectric thin layers.

Keywords: ring resonator, microwave, dielectric, evaluation, thin layer

1. INTRODUCTION

Although microwave (MW) dielectric properties of bulk ceramics have been measured by the Hakki-Coleman method [1] and other resonance methods, the accurate measurement technique of microwave dielectric properties of thin layers is required in late years because passive components of bulk ceramics are recently replaced with of thin or thick film components in order to reduce the size and to increase the integration rate of devices. Some methods have been proposed so far [2-4], however sample sizes are limited by size of the resonators in these methods. On the contrary, we have been developing the impedance method using micro-sized planar electrodes for evaluation of microwave dielectric property of thin layers [5]. This method gives the response of specimens continuously as a function of frequency, while the conductor loss is not negligible with increase of frequency in microwave region. Therefore, in this research, we aimed to develop the novel method for the evaluation of microwave dielectric properties of thin layers, which makes it possible to cancel out the effect of conductor loss and radiation loss in the measurement system. We focused on the ring resonator in this research. The ring resonator is usually applied to a resonator wavelength filter and other high frequency devices. Fig. 1 shows the schematic diagram of the measurement system in this research. In this measurement, TE (Transverse Electric) mode waves are excited in a direction perpendicular to the surface of a sample (Fig.2) on a specific resonance frequency. Therefore, dielectric permittivity and loss tangent in *c* axis directions of a sample could be evaluated in this measurement. The shape of the ring resonator was first designed by the electromagnetic simulation using finite integrate time domain method.

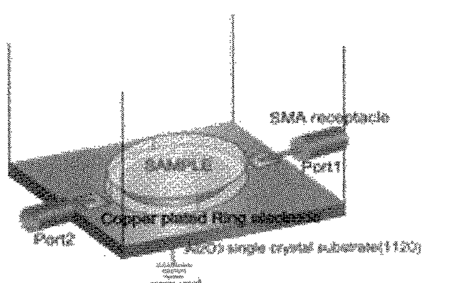

Figure 1. Measurement system of the ring resonator method.

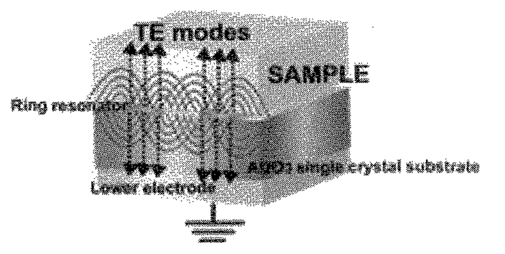

Figure 2. Excited TE mode resonances inside the dielectrics.

2. EXPERIMENT

2-1 Design of the ring resonator using a high frequency electromagnetic field analysis

A top view of the two-port ring resonator applied in this study is shown in Fig. 3, where r is the mean radius of the ring resonator, W is its width, and S is the length of the coupling gap. The configuration of the ring resonator electrode was designed using the electromagnetic field analysis software (CST, MW-Studio, [6]). The mean diameter of the ring resonator r was determined as 3.0 mm. In this analysis, transmission S parameter (S21) as a function of frequency and electric field distributions at the boundary position between the surface of the ring resonator and a sample at resonance frequencies were calculated in GHz region. The simulated resonance peaks of S21 were observed at a constant frequency. The calculated electric field distribution on the ring resonator with a dielectric sample is shown in Fig.4. A stationary wave was observed on a specific resonance frequency with a dielectric sample. The TE mode resonances in the ring resonator are excited, while meeting the following condition [7].

$$l = \lambda_g / n = c / (f (\varepsilon_{eff} (f))^{1/2}) \quad (1)$$

Where, l is circumference of the ring resonator, λ_g is the guided wavelength and n is the order of the resonance and ε_{eff} is the effective dielectric permittivity of the ring resonator. The effective permittivity ε_{eff} is given by Hammerstad and Bekkadal equation [8].

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{ \left(\frac{1}{1+12h/W}\right)^{0.5} + 0.04(1-W/h)^2 \right\} \quad (2)$$

Here, ε_r is the dielectric permittivity of a dielectric substrate and h is the thickness of a dielectric substrate. The resonance frequencies without any samples could be calculated exactly using above two equations. However, ε_{eff} could not be determined directly because the measurement system in this study is not a single dielectric layer model as shown in Fig. 2. Therefore, the resonance frequencies with a sample were evaluated with fitting technique using a high frequency electromagnetic analysis as described later.

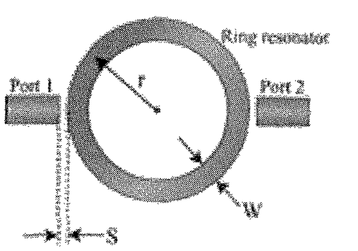

Figure 3. Two-port ring resonator applied in this research.

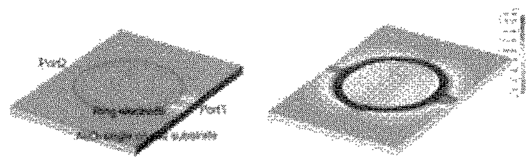

Figure 4. Electric field distributions at the boundary between the ring resonator and a dielectric sample (*left* : non resonant mode at 1 GHz, *right* : resonant mode at 5.5 GHz, ε_r= 10.0).

2-2 Fabrication of the ring resonator and manufacturing the measurement jigs

The ring resonator was formed on a Al_2O_3 single crystal substrate (1120), (ε_r= 9.5, SHINKOSHA CO. LTD.). We selected the pattern electroplating method in fabricating the ring resonator electrode. The pattern electroplating method needs an appropriate ground metal that can be good conductor and chemically etched because the excess ground metal should be removed selectively after copper electroplating on the pattern that separates from the electrode. Firstly, aluminum was coated on the Al_2O_3 single crystal substrate using RF magnetron sputtering. Then resist coating, the ring pattern alignment and development were performed using photolithography method. After forming gold patterns using the DC sputtering and the lift-off method, the copper layer was electroplated. As a final step, aluminum ground layer was etched using the alkali solution. As a result, the copper/gold/aluminum electrode with thickness of 1.05 μm was obtained as shown in Fig. 5. On another front, the measurement jig was also designed and manufactured. SMA (Sub Miniature-type-A) coaxial receptacles were employed as the power insertion ports (Fig. 6).

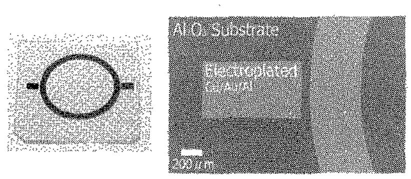

Figure 5. Fabricated ring resonator (*left*) and a SEM image of the resonator (*right*).

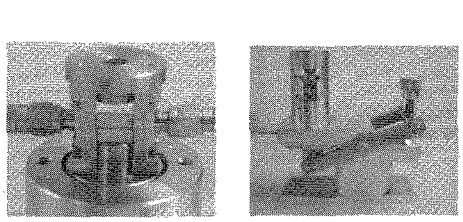

Figure 6. Measurement cell (*left*) and the figure of the equipment (*right*).

2-3 Transmission measurement in MW region

A $SrTiO_3$ single crystal substrate (100) (SHINKOSHA CO. TLD.), the ceramics thin plates of a $SrTiO_3$ and a $SrZrO_3$ were employed as samples first. The ceramics samples were grinded up to the asperity of 0.5 μm with diamond slurry (Engis, Hyprez diamond slurry) before the transmission measurements. Firstly, the transmission S parameters (S21) without any samples were measured with a vector network analyzer (Anritsu, 37397C), (Fig.7). Before the measurement, open, short and load calibrations for the coaxial cables were performed using the coaxial connectors standard kits (Anritsu). As a result, good fitting between resonance frequencies of simulated and those measured was observed up to the fourth (n = 4) resonance frequency (near 25 GHz). It was confirmed that the accuracy of the simulation in this study was sufficiently reliable. Moreover, Q-values were calculated using the following equation with the half bandwidths at each resonance peak of this transmission spectrum without any samples.

$$Q = \frac{f_0}{\Delta f_0} \qquad (3)$$

Where, f_0 is a resonance frequency and Δf_0 is a half bandwidth of a resonance peak. The approximated line for Q-value in the background measurement system as a function of frequency up to 25 GHz was obtained. Here, calculated Q-value includes the radiation loss of the measurement system and the conductor loss of the ring resonator ($Q_r + Q_c$).

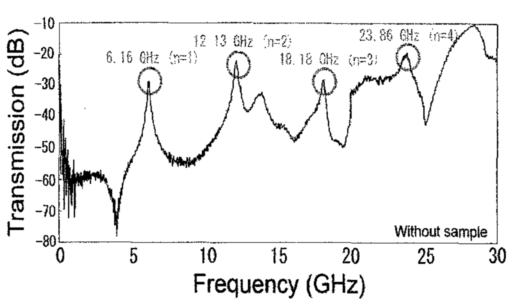

Figure 7. Transmission spectrum without any samples up to the frequency of 30 GHz.

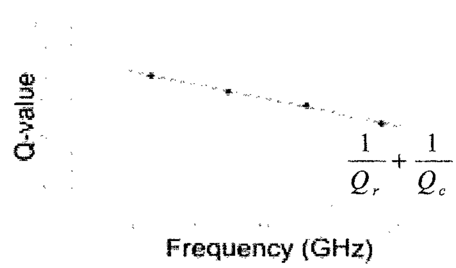

Figure 8. Approximated line of Q-value for the background spectrum as a function of frequency up to 30 GHz.

3. RESULTS AND DISCUSSION

3-1 Evaluation of dielectric permittivity using the electromagnetic analysis

The transmissions S21 with samples were first measured in microwave region, while the samples being pressed on the ring resonator was formed on a sapphire substrate. Fig. 9 shows the observed transmission spectrum with a $SrZrO_3$ ceramics up to the frequency of 30 GHz. The calculated transmission spectrum using the electromagnetic field analysis was also shown in Fig. 9. The trial-and-error process was carried out in order to fit the dielectric permittivity of samples. Dielectric permittivity of a sample at each resonance frequency was evaluated, while comparing the resonance frequencies of measured and those simulated. One dielectric permittivity was taken into account in simulation until the simulated resonance frequency corresponds with that measured. The evaluated dielectric permittivites of samples were in agreement with reference values as shown in Table.1. This result indicates that the ε_r can be correctly evaluated by the ring resonator method.

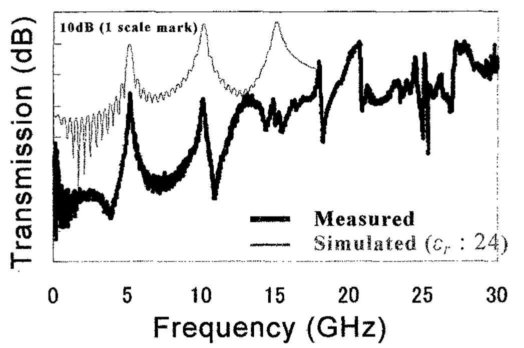

Figure 9. Transmission spectrum with a $SrZrO_3$ ceramics up to 30 GHz.

3-2 Evaluation of Q-values of samples

The conductor loss is not negligible in microwave region, since the conductivity of an electrode changes as a function of frequency because of the skin effect. Moreover, the radiation loss increases with increase of the frequency. Therefore, it was essential to remove the conductor loss and the radiation loss for the accurate evaluation of Q-values of samples. The total Q-value Q_t of the measurement system with a sample is given by following equation [9]

$$\frac{1}{Q_t} = \frac{1}{Q_d} + \frac{1}{Q_r} + \frac{1}{Q_c} \qquad (4)$$

where, Q_t is Q-value in the total measurement system, Q_d is Q-value of dielectrics, Q_r is a Q-value of radiation loss, and Q_c is a Q-value of the conductivity loss of the ring resonator. The Q-value of a sample; Q_d at each resonance frequency could be evaluated, while subtracting $1/Q_r$ and $1/Q_c$ from $1/Q_t$. The evaluated Q_d-values of samples were shown in Table.1. Evaluated Qf-values were in good agreement with those reported.

3-3 Evaluation of MW dielectric property of a thin layer using this novel method

It was confirmed that dielectric property of a bulk ceramics in microwave region could be evaluated by this novel method developed in this study. Therefore, microwave dielectric property of a dielectric thin layer was evaluated using this method at last. A ceramics/polymer composite thick film that has thickness of 66 μm was employed as a sample. Fig. 10 shows the observed transmission spectrum with a film and that simulated. The simulated spectrum was obtained, while taking ε_r = 2.4 into account. The dielectric permittivity and Qf-value of the thick film were evaluated as shown in Table.1.

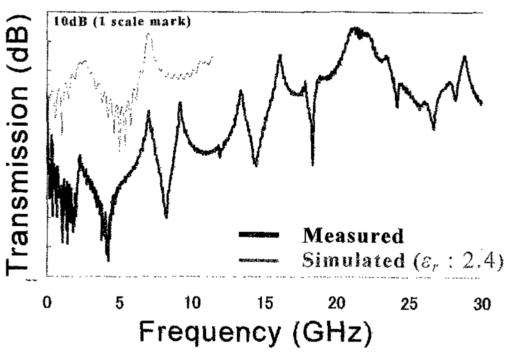

Figure 10. Transmission spectrum with a ceramics/polymer composite thick film up to 25 GHz

Table 1. Evaluated MW dielectric properties by this method and those reported

	ε_r	Qf (GHz)
$SrTiO_3$ single crystal (100) This study	320 (3.95GHz)	2478
Reported [10]	310 (1 MHz)	3000
$SrTiO_3$ ceramics This study	275 (8.74 GHz)	2020
Reported [11]	290 (1.2 GHz)	3000
$SrZrO_3$ ceramics This study	24 (14.9 GHz)	11682
Reported [12]	38 (11 GHz)	13600
Ceramics/Polimer composite thick film This study	2.4 (7.03 GHz)	1256
Reported	3.4 (1 GHz)	—

CONCLUSION

We investigated the possibility to estimate the dielectric property of dielectric thin layers accurately using the developing ring resonator method. In this method, the conductor loss of the metal electrode and the radiation loss in microwave region could be removed, while subtracting Q-values measured without any samples from those measured with samples. Consequently, dielectric permittivities and Qf-values in microwave region were both evaluated accurately in some bulk thin ceramics and a ceramics/polymer composite thick film. This result indicated the novel method would be applied to the practical tool for the evaluation of dielectric property of thin layers in microwave region.

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