DYNAMICM MEASUREMENT OF THE TEMPERATURE CHARACTERISTIC OF DIELECTRIC MATERIAL FOR MICROWAVE APPLICATION USING PHOTO THERMAL DIELECTRIC MICROSCOPE

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ABSTRACT

A new photo thermal technique for measuring the temperature characteristic of dielectric material for microwave application is proposed. It is based on the temperature characteristic of the dielectric constant of light irradiated material. When a dielectric material is illuminated with chopped light, an alternating variation of capacitance is caused by the heat produced due to light absorption and this variation is detectable with enough dynamic range and sensitivity. First, quantitative derivations are presented for the alternating capacitance variation in terms of the optical, thermal, dielectric and geometric parameters of the system. Next, a very high sensitive type of PTDM using the coaxial cavity resonator with operating frequency of microwave range is developed. Using this microscope,the temperature characteristics of the binary-system TiO_2-Bi_2O_3 dielectric ceramics for microwave application are successfully measured.

INTRODUCTION

Recently, we have found that when a dielectric material is illuminated with chopped light, an alternating variation of the dielectric constant is caused by the local temperature rising of it due to light absorption and this variation is detectable with enough dynamic range and sensitivity.

Using this photo thermal dielectric (PTD) effect, new type of spectroscope (photo thermal dielectric spectroscope: PTDS) and microscope (photo thermal dielectric microscope : PTDM) are obtainable This method has the advantages over the conventional photo acoustic spectroscopy (PAS)[1][2] that every phenomenon can be explained quantitatively and that the response by this method is rapid and the measurement in a vacuum is possible. Moreover, since the principle is based on the temperature characteristic of the dielectric constant, the measurement of the microscopic distribution of the temperature coefficient of the dielectric constant for dielectric materials may be possible.

In this paper, we present the basic theory describing the PTD effect and the development of a PTDM for the measurement of the temperature coefficients of the dielectric materials which are used for microwave devices. First, we theoretically derive the alternating capacitance variation due to light absorption for the one- and two-dimensional models for the PTD signals in terms of the optical, thermal, dielectric and geometric parameters of the system. Especially, in one-dimensional model,the simple representations of the six special cases for the PTD theory of solid are obtained. Next, a highly sensitive type of PTDM operating at the microwave frequency range is developed and the temperature characteristics of the binary-system TiO_2-Bi_2O_3 dielectric ceramics[3] for microwave application are successfully measured.

THEORETICAL STUDIES ON THE PHOTO THERMAL DIELECTRIC EFFECT WITH SOLID

Now, we consider the following situation that the alternating temperature change due to the absorption of chopped light with angular frequency ω_c causes the alternating variation of capacitance because of its temperature characteristics. Figure 1 shows the one-dimensional model for the analysis of the production of a PTD signal. When the static temperature variation and the alternating one from the room temperature T_0 due to an irradiation of light are expressed by $\Delta T_{dc}(x)$ and $T_{ac}(x,t)$, the temperature in the specimen $T(x,t)$ and the dielectric constant $\varepsilon(x,t)$ are given by

$$T(x,t) = T_0 + \Delta T_{dc}(x) + T_{ac}(x,t) \quad (1)$$

$$\varepsilon(x,t) = \varepsilon(T_0)+\varepsilon'(T_0)(\Delta T_{dc}(x)+T_{ac}(x,t)) \quad (2)$$

where $\varepsilon(T_0)$ and $\varepsilon'(T_0)$ are the dielectric constant and its first order temperature coefficient at room temperature, re-

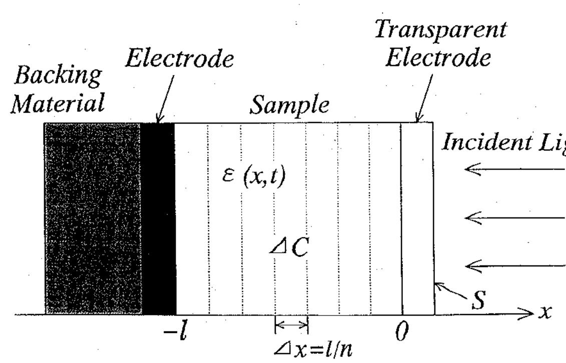

Fig.1 The one-dimensional model for photo thermal dielectric signal.

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spectively. As shown in Fig.1, we consider the n-divided portion of capacitance ΔC made of a measuring material whose value is

$$\Delta C = \varepsilon(x,t)\frac{S}{\Delta x} \qquad (3)$$

$$\Delta x = \frac{\ell}{n} \qquad (4)$$

where S and ℓ denote the area and the thickness of specimen, respectively. Because these divided capacitances are connected each other in series, the combined capacitance C is expressed by

$$C = \frac{1}{\sum \frac{1}{\Delta C}} \qquad (5)$$

Here, we take the limit of $n \rightarrow \infty$ and obtain the resultant value of C as

$$C = \lim_{n\rightarrow\infty} \frac{1}{\sum \frac{1}{\Delta C}} = \frac{S}{\int_{-\ell}^{0} \frac{1}{\varepsilon(x,t)} dx} \qquad (6)$$

Substituting eq.(2) into eq.(6), we obtain the capacitance irradiated by the chopped light as

$$\begin{aligned} C &= C(T_0) + \Delta C_{dc} + C_{ac} \\ &= \varepsilon(T_0)\frac{S}{\ell}[1 + \frac{1}{\ell}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_{-\ell}^{0}\{\Delta T_{dc}(x) + T_{ac}(x,t)\}dx] \end{aligned} \qquad (7)$$

$$C(T_0) = \varepsilon(T_0)\frac{S}{\ell} \qquad (8)$$

$$\Delta C_{dc} = C(T_0)\frac{1}{\ell}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_{-\ell}^{0}\Delta T_{dc}(x)dx \qquad (9)$$

$$C_{ac} = C(T_0)\frac{1}{\ell}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_{-\ell}^{0} T_{ac}(x,t)dx \qquad (10)$$

where $C(T_0)$, ΔC_{dc} and C_{ac} show the capacitance at room temperature T_0, the static capacitance variation and dynamic(alternating) one, respectively.

In case of the two dimensional model shown in Fig.2, we should take the temperature variation along the radius r

$$T(r,x,t) = T_0 + \Delta T_{dc}(r,x) + T_{ac}(r,x,t) \qquad (11)$$

into consideration. The capacitance $\Delta C(r)$ of the tours portion among $r \sim r + dr$ can be obtained by changing S in eq.(7) to $dS = 2\pi r dr$, that is

$$\begin{aligned} &\Delta C(r) \\ &= \varepsilon(T_0)\frac{2\pi r}{\ell}[1 + \frac{1}{\ell}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_{-\ell}^{0}\{\Delta T_{dc}(r,x) + T_{ac}(r,x,t)\}dx]dr \end{aligned} \qquad (12)$$

In this case, as these $\Delta C(r)$s are connected in parallel, the finally obtained combined capacitance C is expressed by summing up these $\Delta C(r)$s as

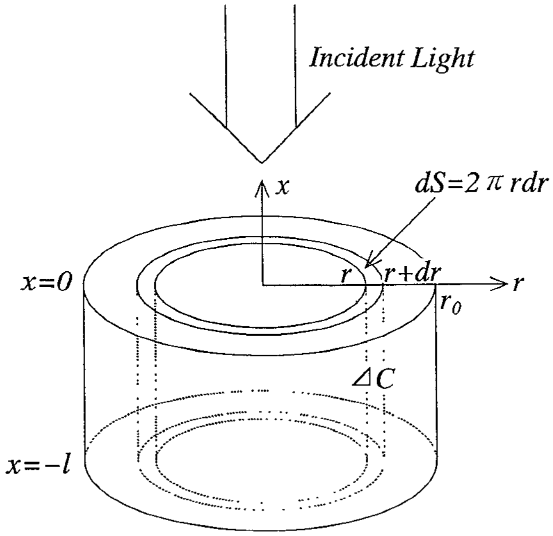

Fig.2 The two-dimensional model for photo thermal dielectric signal.

$$C = \int_0^{r_0} \Delta C \qquad (13)$$

where r_0 is the radius of the specimen. Thus, we have the final formulas for two dimensional model corresponding to eq.(8),(9) and(10) as

$$C(T_0) = \varepsilon(T_0)\frac{\pi r_0^2}{\ell} \qquad (14)$$

$$\Delta C_{dc} = C(T_0)\frac{2}{\ell r_0^2}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_0^{r_0}\int_{-\ell}^{0} r\Delta T_{dc}(r,x)dxdr \qquad (15)$$

$$C_{ac} = C(T_0)\frac{2}{\ell r_0^2}\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\int_0^{r_0}\int_{-\ell}^{0} rT_{ac}(r,x,t)dxdr \qquad (16)$$

Table I shows the evaluation the eq.(10) in the six special cases of capacitance variation obtained by using the theory of Rosencwaig for PAS[2], where $\rho_s, c_s, k_s\mu_s$ and ω_c are the density, the specific heat, the thermal conductivity, and the thermal diffusion length of the Sample, respectively and ρ_b, c_b and k_b are corresponding parameters of the backing material. β, μ, ω_c and I_0 denote the optical absorption coefficient, the optical absorption length, the chopping angular frequency of the incident light beam and the light intensity, respectively. In this theoretical calculation, we assume that the gas and backing materials are not light absorbing[2].

DEVELOPMENT OF HIGHLY SENSITIVE TYPE OF PTDM AND MEASUREMENT OF THE TEMPERATURE CHARACTERISTIC OF DIELECTRIC CERAMICS FOR MICROWAVE APPLICATION

Next, we describe the development of a highly sensitive type of the PTDM. The schematic diagram of this PTDM is shown in Fig.3. To measure the capacitance variation with

Table I The alternating capacitance for six special cases

Optically Transparent Solids ($\mu > \ell$)	Optically Opaque Solids ($\mu \ll \ell$)
Thermally Thin Solids ($\mu_s \gg \ell, \mu_s > \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0\beta\ell}{2\sqrt{k_b\rho_b C_b}}\frac{1}{\sqrt{\omega}}\cos(\omega_c t - \frac{\pi}{4})$	Thermally Thin Solids ($\mu_s \gg \ell, \mu_s \gg \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0}{2\sqrt{k_b\rho_b C_b}}\frac{1}{\sqrt{\omega}}\cos(\omega_c t - \frac{\pi}{4})$
Thermally Thin Solids ($\mu_s > \ell, \mu_s < \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0\beta\ell}{2\sqrt{k_b\rho_b C_b}}\frac{1}{\sqrt{\omega}}\cos(\omega_c t - \frac{\pi}{4})$	Thermally Thick Solids ($\mu_s < \ell, \mu_s > \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0}{2\ell\rho_s C_s}\frac{1}{\omega}\cos(\omega_c t - \frac{\pi}{2})$
Thermally Thick Solids ($\mu_s < \ell, \mu_s \ll \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0\beta}{2\rho_s C_s}\frac{1}{\omega}\cos(\omega_c t - \frac{\pi}{2})$	Thermally Thick Solids ($\mu_s \ll \ell, \mu_s < \mu$) $C_{ac} = C(T_0)\frac{\varepsilon'(T_0)}{\varepsilon(T_0)}\frac{I_0}{2\ell\rho_s C_s}\frac{1}{\omega}\cos(\omega_c t - \frac{\pi}{2})$

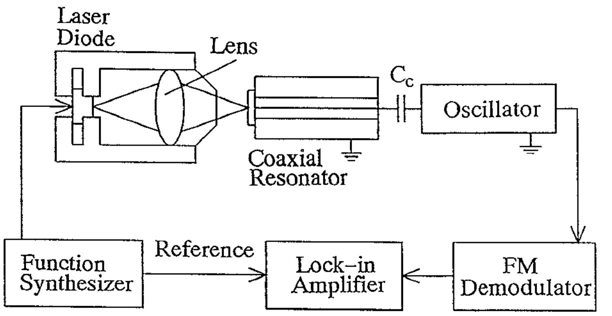

Fig.3 Schematic diagram of the photo thermal dielectric microscope for the temperature coefficient of dielectric material for microwave application.

chopped light, we developed a new probe for PTDM using the coaxial cavity resonator with the capacitor C made of the material to be measured as shown in Fig.4. This cavity has the resonance frequency at the microwave frequency range and the oscillator oscillates at the very close frequency to the resonant frequency.The electrode of one side of the capacitor is transparent and is made of an indium tin oxide (ITO) thin film or a very thin gold film (~200Å). The alternating temperature change due to the absorption of chopped light with angular frequency ω_c causes the alternating variation of capacitance because of its temperature characteristic so that the oscillator frequency is modulated alternately by the change of the capacitance. As a result, frequency modulation (FM) signal comes from this oscillator . By detecting this FM signal using the FM demodulator and the Lock-in amplifier, we can obtain the voltage signal which is proportional to the capacitance variation. In general, the sensitivity of FM demodulator is directly proportional to the frequency deviation Δf only and this Δf is proportional to the carrier frequency f_0. Thus, it is understood that we can obtain the more highly sensitive PTDM by using a higher oscillating frequency. The equivalent circuit expression of Fig.4 is shown in Fig.5. The resonant condition of this cavity and the relationship between the resonant frequency variation $\Delta\omega$ and the alternating capacitance variation C_{ac} are respectively expressed as

$$\omega_0 C = -Y_0 \tan \gamma_0 d \quad (17)$$

$$\frac{\Delta\omega}{\omega_0} = -\frac{C_{ac}/C}{1 + (d/Cv)Y_0 \mathrm{cosec}^2\gamma_0 d} \quad (18)$$

where Y_0, d and γ_0 ($=\omega_0/v$: v=velocity of microwave) are the characteristic admittance, the length and the propagation constant of the coaxial line , respectively.

Applying this highly sensitive type PTDM to evaluate of the temperature characteristics of dielectric ceramics at the microwave frequency range, we performed some exper-

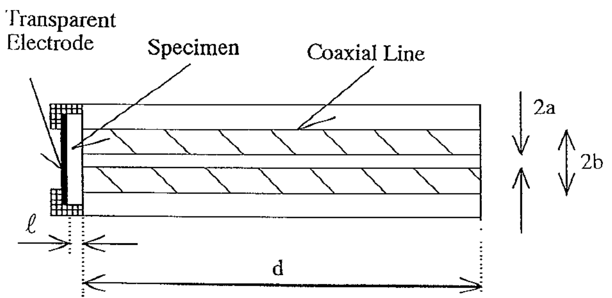

Fig.4 Coaxial cavity resonator for the probe of highly sensitive PTDM.

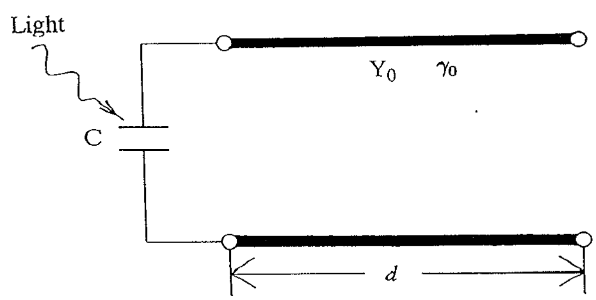

Fig.5 Equivalent circuit expression of Fig.4.

Table II Microwave characteristics of TiO_2-Bi_2O_3 ceramics[3]

Sample	Composition(mol%)		Chemical formula	Dielectric properties		
	TiO_2	Bi_2O_3		ε_r	Q(at 5GHz)	τ_f(ppm/°C) (0~50°C)
A	100	0	TiO_2	105.0	9200	+465
B	91.9	8.1	TiO_2-$Bi_2Ti_4O_{11}$	80.0	1800	+21
C	80.0	20.0	$Bi_2Ti_4O_{11}$	53.2	900	−550

iments for optically opaque and thermally thick materials. As the specimens, we used the binary-system TiO_2-Bi_2O_3 ceramics[3], whose compositions and the microwave characteristics are summarized in Table II.

Firstly, PTD signals vs. light chopping frequency at room temperature for these three ceramics were measured. The sign of the temperature coefficient of dielectric constants $\varepsilon'(T_0)$ is positive for the sample A and B, whereas negative for C. In this experiment and mentioned below, we used a diode Laser with the power of 20mW and wavelength of $\lambda = 685$nm as the light source and the oscillating frequencies were about 1.3GHz. The results are shows in Fig.6. In the case for sample A and B, the phase of the demodulated signal was almost +90°, and for the sample C it was −90°, without chopping frequency dependency. In contrast to this, the amplitudes were proportional to the reciprocal of the chopping frequency. These phase and amplitude obtained by this experiment show good agreement with the equation for optically opaque and thermally thick material in Table I, too.

Finally, we directly measured the temperature dependence of the resonant frequency coefficient τ_f of the sample B using this PTDM. At the same time, the temperature dependence of the resonant frequency was also measured. Of course, the former data should agree with the first derivative of the latter with respect to the temperature. These results are shown in Fig.7 and agree very well each other.

Thus, we can find that the temperature characteristics of dielectric materials such as the temperature with zero temperature coefficient τ_f=0, etc., are easily and precisely obtainable by using our proposed PTDM.

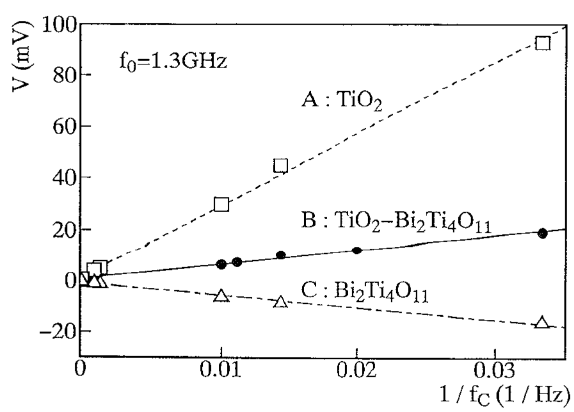

Fig.6 PTD signals vs. reciprocal of light chopping frequency for several dielectric ceramics for microwave application.

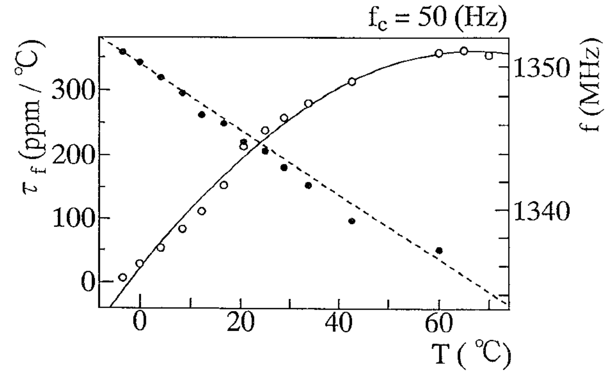

Fig.7 The temperature dependence of the temperature coefficient τ_f of resonant frequency of TiO_2-$Bi_2Ti_4O_{11}$ ceramics measured by PTDM (solid circle •) and the resonant frequency (open circle o). Dashed line denotes the first derivative of the resonant frequency with respect to temperature.

CONCLUSION

We have proposed new photo thermal technique using photo thermal dielectric effect. First,we presented the basic thory for the PTD signal. Next, a highly sensitive type of PTDM is developed. Using this PTDM, we successfully measured the temperature characteristics of the dielectric ceramics for microwave application. Since the microscopic distribution of temperature coefficient can be observed using this technique, we will be able to obtain the temperature coefficient of dielectric constant of each grain in the composite ceramics.

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