INTERNATIONAL MICROWAVE POWER INSTITUTE'S
40TH ANNUAL SYMPOSIUM

PROCEEDINGS

ISSN: 1070-0129

AUGUST 9-11, 2006
BOSTON, MASSACHUSETTS, USA

AN IMPI PUBLICATION

COAXIAL LINE REFLECTION METHOD FOR DIELECTRIC PERMITTIVITY OF THIN FILM SAMPLES AT MICROWAVE FREQUENCIES: NUMERICAL AND EXPERIMENTAL ANALYSIS

J. Obrzut

National Institute of Standards and Technology, Gaithersburg, MD, USA

We describe a measurement method for broadband dielectric permittivity of thin film materials at microwave frequencies utilizing a small-gap shunt capacitor terminating a coaxial line. The model expression for input impedance takes into consideration the wave propagation and inductance of the specimen section, and correlates the network parameters with the complex permittivity of the specimen. The method is suitable for testing dielectric materials having nominal thickness between 1 μm to 300 μm at frequencies of 100 MHz to 12 GHz and a dielectric constant of up to 60. With proper calibration and computation the frequency range can be extended to 18 GHz.

INTRODUCTION

A measurement configuration using a parallel plate capacitor terminating a coaxial waveguide (transmission line) has been widely used in broadband complex permittivity measurements. In this configuration, often referred to as a lumped capacitance method, a dielectric disk or rod sample of the diameter of the center conductor is placed at the end of coaxial waveguide as a capacitive termination [Stuchly and Stuchly, 1980]. This technique is accurate up to a frequency at which the input impedance of the specimen decreases to one tenth (0.1) of the characteristic impedance of the coaxial line [Iskander and Stuchly, 1978]. This upper frequency limit is lower for thinner specimens that have a higher dielectric constant. For a 100 μm thick specimen with a dielectric constant of about 60, measured in the APC-7 configuration, the upper frequency limit falls to within 85 MHz. This is well below the desirable frequency range of about 10 GHz.

In our earlier work we analyzed the wave propagation in the film specimen terminating a coaxial line. We considered it as a distributed component having complex capacitance with residual inductance, for which we formulated an expression for the input impedance [Obrzut, Noda and Nosaki, 2002; Obrzut and Anopchenko, 2004]. In this paper, we present an application of this expression to measure complex permittivity of thin film dielectric materials at frequencies of up to 12 GHz.

Key words: Dielectric Materials, High Frequency Measurements, Coaxial Discontinuity

ANALYSIS

At frequencies where the specimen may be treated as a lumped capacitance, the input impedance $\mathbf{Z}_{in}$ is given by expression (1) [Stuchly and Stuchly, 1980; Iskander and Stuchly, 1978]:

$$\mathbf{Z}_{in} = \frac{1}{\mathbf{j}\omega C_p \varepsilon_r^*} = Z_0 \frac{1+\mathbf{S}_{11}}{1-\mathbf{S}_{11}} \tag{1}$$

S_{11} is the directly measured one-port scattering coefficient, $\omega = 2\pi f$ is the angular frequency, and C_p is the specimen geometrical (air filled) capacitance., $C_p = \varepsilon_0 (\pi\, d^2/4t)$, d is the specimen diameter, and t is the thickness of the dielectric specimen. Permittvities ε_0 and $\varepsilon_r^* = \varepsilon' - j\varepsilon''$ are that of air and the specimen material respectively. At low frequencies, the real (ε') and imaginary (ε'') component of the complex dielectric permittivity can be obtained directly from analytical solution of equation (1), where the upper frequency limit is typically below 1 GHz [Iskander and Stuchly, 1978]. However, at higher microwave frequencies, the specimen section represents a network of a transmission line with capacitance $C_p\varepsilon_r^*$, in which the electromagnetic field is no longer spatially uniform due to super position of multiple wave reflections. The three-dimensional spatial distribution of electric field in the specimen section, obtained by solving Maxwell's equations using a finite element High Frequency Structure Simulator (Ansoft HFSS), is shown in Fig.1.

The electric field has a radial symmetry, while the propagation direction is along the diameter of

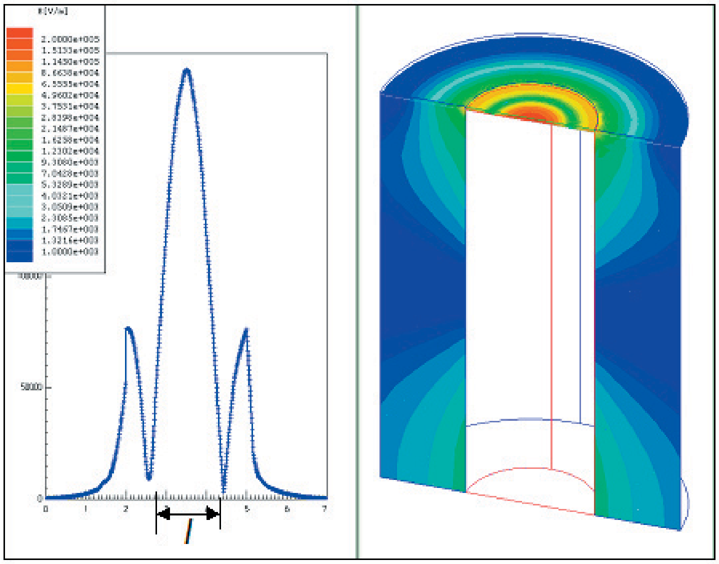

Figure 1. *Spatial distribution of the electric field in the specimen section at the resonant frequency* f_{cav}.

the specimen rather than its thickness. The results of numerical simulations indicate that the propagation length $l = 0.823d$, which is a little smaller then the specimen diameter. Thus, the boundary conditions are affected by the fringing field and do not correspond directly to the boundaries resulting from the specimen geometry. Moreover, we determined that the specimen residual inductance L_s, is a linear function of the specimen thickness, L_s=1.27 10 $^{-7}$ [H / m] x t [m]. It has been commonly accepted that for thin film specimens the inductive component is negligibly small, and the electrical characteristic is dominated by its complex capacitance. Most analytical work on coaxial discontinuities applied this assumption to simplify the corresponding theoretical model [Navarro, 1991; Eom, Noh and Park, 1998]. However, our results indicate that L_s can considerably influence the impedance characteristic, especially in the vicinity of the series resonant frequency, and therefore it cannot be neglected. The input impedance of the specimen, calculated according to the propagation model with L_s contribution to Z_{in} leads to the following general expression:

$$\mathbf{Z}_{\text{in}} = \frac{\mathbf{x}\cot(\mathbf{x})}{\mathbf{j}\omega C_p \varepsilon_r^*} + \mathbf{j}\omega L_s \qquad (2)$$

where $\mathbf{x} = \omega l \sqrt{\varepsilon_r^*} / 2c$. Expression (2) has a minimum at the series resonant frequency, f_{LC}, followed by a maximum at the first cavity resonant frequency f_{cav}, when $x = \pi$. It is worthy to note that at low frequencies, below f_{LC}, the propagation term $\boldsymbol{x}$ *cot* ($\boldsymbol{x}$) approaches 1, the term ωL_s is small and can be neglected, and (2) simplifies to well known formula (1) for a shunt capacitance, $C_p \varepsilon_r^*$, terminating a coaxial transmission line. Comparing the right side of equations (1) with (2) leads to (3), which relates the complex dielectric permittivity, ε_r*, of the test specimen with the measurable scattering parameter $\boldsymbol{S}_{11}$.

$$\varepsilon_r^* = \frac{x\cot(x)}{\mathbf{j}\omega C_p (Z_0 (1+\mathbf{S}_{11})/(1-\mathbf{S}_{11}) - \mathbf{j}\omega L_s)} \qquad (3)$$

Because the propagation term x depends on permittivity, (3) does not have direct analytical solution and needs to be solved iteratively. Description of a suitable procedure can be found in the reference [Korn and Korn, 1968].

Typically, it requires between five to twenty iterations to reach the terminating criterion. Commercially available software can be used to program and automate the computational steps 1 through 3 and solve (7) numerically for ε_r* and the corresponding uncertainty values. The software should be capable of handling simultaneously both the real and the imaginary part of complex $\boldsymbol{S}_{11}$, x *cot* (x) and ε_r*.

EXPERIMENT

The implemented test fixture consists of two sections *A* and *B*, where the specimen is placed in between. Section *A* is an APC-7 to an APC-3.5 microwave adapter with characteristic impedance of 50 Ω (Agilent 1250-1746). Section B is an altered APC-7 short termination (Agilent

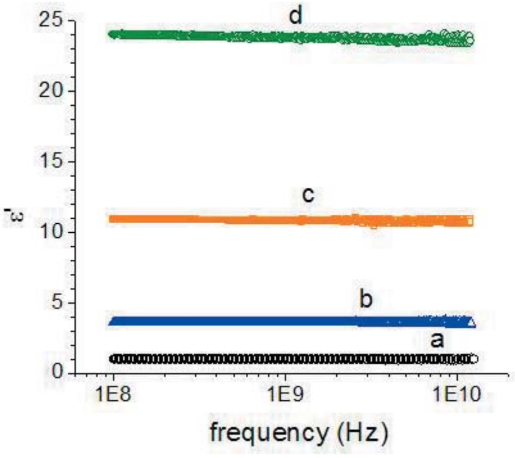

Figure 2. *Dielectric constant, ε' of film specimens. (a): 2 μm air-gap; (b) 50 μm thick film with the nominal value of ε' of 3.5; (c) 25 μm thick film ε' of 11; (d) 8 μm thick film ε' of 24.*

04191-85300 or equivalent may be used), with a custom-machined gap to accommodate a specimen of particular thickness. When sections *A* and *B* are assembled, the depth of the gap equals the specimen thickness. The test specimen consists of a circular disk capacitor having the nominal diameter, *d*, of 3.0 mm with metal electrodes on both sides. Measurements were performed by using an automatic vector network analyzer, Agilent 8720D operating in the frequency range of 100 MHz to 18 GHz. Connection between the test fixture (APC 3.5 adapter of section A) and the network analyzer was made using a phase preserving coaxial cable, Agilent 85131-60013. Open, Load, Short calibration was performed using Agilent 85050B 7 mm calibration standard.

RESULTS AND DISCUSSION

The results of the dielectric constant measurements are illustrated in Figure 2 for dielectric films having nominal dielectric constant values of 3.5, 11 and 24 respectively. Figure 2a shows the dielectric constant of a 2 μm air-gap, $\varepsilon'_a = 1$, measured from 100 MHz to about 12 GHz.

In the frequency range of up to 10 GHz (Fig. 2) the relative uncertainty, $(\Delta\varepsilon'_a)/\varepsilon'_a$, determined as a deviation from the standard value of 1.00 is below 2 %. The combined uncertainty for the dielectric loss, $\Delta\varepsilon''_a$, is estimated to be less than 0.01 in the same frequency range. At higher frequencies, above 10 GHz the uncertainty increases to about 5 % By using appropriate calibration standards, the APC-7 test fixture configuration may be utilized in the frequency range of 100 kHz to 18 GHz. The computational algorithm and in particular equations (3) has been validated up to the first cavity resonance frequency, f_{cav}, which is determined by the propagation length *l*, and the dielectric constant of the specimen: $f_{cav} = c/(l\,\mathrm{Re}(\sqrt{\varepsilon_r^*})) \approx 121/(\sqrt{\varepsilon_r}\ [GHz]$ where Re indicates the real part of complex square root of permittivity and *l* =2.47 mm. For example, in the case of a specimen having the dielectric constant of 100, f_{cav} is about 12 GHz. Several uncertainty factors such as instrumentation, the dimensional uncertainty of the test specimen geometry, roughness and conductivity of the conduction surfaces contribute to the combined uncertainty of the measurements. The complexity of modeling these factors is considerably higher within the frequency range of the LC resonance. Adequate analysis can be performed, however, by using the partial derivative technique [Iskander and Stuchly, 1978] for equations (1) and considering the instrumentation and the dimensional errors. The standard uncertainty of $\boldsymbol{S}_{11}$ can be assumed to be within the manufacturer's specification for the network analyzer, about ± 0.005 dB for the magnitude and ± 0.5 ° for the phase. The combined relative standard uncertainty in geometrical capacitance measurements is typically smaller than 5 %, where the largest contributing factor is the uncertainty in the film thickness measurements. Equation (4) for the residual inductance has been validated for specimens 8 μm to 300 μm thick. Measurements in the frequency range of 100 MHz to 12 GHz are reproducible with relative combined uncertainty in ε'and ε" of better than 8 % for specimens having $\varepsilon' < 80$ and thickness $d < 300$ μm. The resolution in the dielectric loss tangent measurements is < 0.005. Additional limitations may arise from the systematic uncertainty of the particular instrumentation, calibration standards and the dimensional imperfections of the implemented test fixture. Furthermore, results may be not reliable at frequencies where $|\boldsymbol{Z}|$ decreases below 0.05 Ω.

SUMMARY

We developed a coaxial line reflection method for dielectric permittivity of thin film samples at microwave frequencies. Our approach allows overcoming the limits of the lumped capacitance methods and enables accurate complex permittivity measurements of film samples in the extended frequency range up to the first cavity resonance frequency. For example, in the case of a specimen having the dielectric constant of 100 the upper frequency limit is about 12 GHz. The results of our analysis enable the dielectric characterization of thin film materials that are of interest to microelectronics, bio-and nano-technology.

DISCLAIMER

Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

Certain equipment, instruments or materials are identified in this paper in order to adequately specify the experimental details. Such identification does not imply recommendation by the National Institute of Standards and Technology nor does it imply the materials are necessarily the best available for the purpose.

REFERENCES

Eom, H. J., Noh Y.C. and Park J.K. (1998); "Scattering analysis of a coaxial line terminated by a gap", *IEEE Microwave and Guided Wave Lett.* vol. 8, pp 218-19.

Iskander M. F. and Stuchly S. S. (1978), "Fringing field effect in the lumped-capacitance method for permittivity measurements", *IEEE Trans. Instrum. Meas.*, vol. IM-27, pp. 107-109.

Korn G. A. and Korn T. M. (1968), Mathematical Handbook for Scientists and Engineers, McGraw-Hill, 2nd edition pp. 719.

Obrzut J. and Anopchenko A., (2004),"Input impedance of a coaxial line terminated with a complex gap capacitance – numerical and experimental analysis," *IEEE Trans. Instrum. Meas.,* vol. 53, pp. 1197-1202.

Navarro M. S. (1991), "Disk-gap discontinuity in a coaxial transmission line", *Circuits and Systems*, vol. 2, pp. 735-738.

Obrzut J., Noda N. and Nozaki R. (2002), "Broadband characterization of high-dielectric constant films for power-ground decoupling", *IEEE Trans. Instrum. Meas.*, vol. 51, 829-832.

Stuchly M.A. and S. S. Stuchly (1980), "Coaxial line reflection methods for measuring dielectric properties of biological substances at radio and microwave frequencies: A review", *IEEE Trans. Instrum. Meas*., vol. 29, pp. 176-183.