Characterization of Thin-Film Low-Dielectric Constant Materials in the Microwave Range Using On-Wafer Parallel-Plate Transmission Lines

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***Abstract*—A method is presented to measure the dielectric properties of a thin film over a broad microwave frequency range. The parallel-plate transmission line geometry offers both the advantages of pronounced sensitivity to thin-film properties and exact computation of the value of the dielectric constant and the loss tangent. With multiline thru-reflect-line calibration techniques, the dielectric constant and loss tangent are determined to an accuracy better than 4% at 10 GHz.**

***Index Terms*—Dielectric films, permittivity measurement, transmission line measurements.**

I. Introduction

THE rapid growth of integrated technology is primarily based on the continued scaling down of device dimensions. To meet the increased density and performance requirements of next-generation ultra-large-scale-integration devices (gate length $< \ 0.18\ \mu$m), new thin-film dielectric materials are needed with dielectric constants significantly lower than silicon dioxide in the microwave frequency range [1]. Since the physical properties of such thin films are often process and thickness dependent, new methods are required to determine their thin-film dielectric properties at microwave frequencies.

Characterization of the dielectric properties of thick materials in the microwave frequency range has been well developed [2]–[6], but exhibit too low sensitivity to low-dielectric thin films. New broadband microwave characterization methods are needed that are specialized for thin films. The fabrication of the test structures for thin film materials must be compatible with established IC manufacturing procedures. In this paper, we propose and demonstrate the use of parallel-plate microwave transmission-line structures tailored to thin films, and we perform frequency-domain network analyzer measurements to extract the exact dielectric constant in the 1–10 GHz range.

Coplanar waveguide (CPW) and microstrip transmission lines have been used to characterize dielectric materials [7]–[10]. CPW structures are relatively insensitive to thin-film dielectric properties since only a small portion of the electric field is located inside the dielectric layer. Microstrip structures exhibit the so-called slow-wave mode caused by metal losses that complicates the extraction of dielectric properties [11]. For such reasons, we present in this paper a thin-film parallel-plate waveguide structure that concentrates the electric field in the dielectric thin film and can be precisely implemented using fabrication techniques that are compatible with low-dielectric constant thin-film materials. The test structure propagates a well-defined transverse magnetic (TM) mode that has well-understood modal properties and can be rigorously modeled to extract the dielectric properties. The structure consists of a bottom metallic conductor embedded in a dielectric substrate. After spin coating the low-dielectric constant thin film, the top conducting layer is deposited such that the film is between the two metal layers. We use multiline thru-line-reflect (TRL) calibration algorithm to determine the propagation constant and relate it to the dielectric properties of the thin film via the following model.

II. Theory

For transmission-line widths significantly larger than the thickness of the dielectric film, the parallel-plate transmission line is accurately described by the two-dimensional five-layer planar model. Each layer i is characterized by its thickness d_i, complex permittivity ε_i, and permeability μ_i. Layer 1 represents the infinitely thick substrate, layers 2 and 4 the metal layers adjacent to the dielectric thin film (layer 3), and layer 5 is air. The Z direction is the propagation direction and the n direction is normal to the planar interfaces. For TM mode propagation, in each region i the magnetic field is

$$\bar{H}_i = [A_i e^{-jk_0\kappa_i x} + B_i e^{+jk_0\kappa_i x}]e^{-k_0\gamma z}\hat{y} \tag{1}$$

where κ_i is the normalized complex propagation constant in x direction, γ is the normalized complex propagation constant in z direction, $k_o = 2\pi/\lambda_o$, and λ_o is the free-space wavelength. Matching the tangential electric and magnetic fields at the interfaces corresponds to

$$\begin{aligned}\begin{pmatrix}A_1\\B_1\end{pmatrix} &= D_{12}P_2D_{23}P_3D_{34}P_4D_{45}\begin{pmatrix}A_5\\B_5\end{pmatrix}\\ &= \begin{pmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{pmatrix}\begin{pmatrix}A_5\\B_5\end{pmatrix}\end{aligned} \tag{2}$$

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where

$$P_i = \frac{1}{2}\begin{pmatrix} e^{-jk_0\kappa_i d_i} & 0 \\ 0 & e^{+jk_0\kappa_i d_i} \end{pmatrix}, \quad i = 2 \text{ to } 4 \qquad (3)$$

d_i is the film thickness, and

$$D_{(i-1)i} = \frac{1}{2}\begin{pmatrix} 1+\frac{\varepsilon_{i-1}\kappa_i}{\varepsilon_i\kappa_{i-1}} & 1-\frac{\varepsilon_{i-1}\kappa_i}{\varepsilon_i\kappa_{i-1}} \\ 1-\frac{\varepsilon_{i-1}\kappa_i}{\varepsilon_i\kappa_{i-1}} & 1+\frac{\varepsilon_{i-1}\kappa_i}{\varepsilon_i\kappa_{i-1}} \end{pmatrix}, \quad i = 2 \text{ to } 5. \qquad (4)$$

The propagation constants of modes are determined by the condition $M_{11} = 0$ [12]. From this relationship, the permittivity of layer 3 can be calculated if all other parameters are known.

The propagation constant γ is calculated from the scattering parameter (S_{ij}) measurements taken from multiple transmission lines with different lengths. The transverse geometry of the structures is identical. Without any system calibration or any calibrated references, the propagation constant is calculated from the scattering parameters taken from two different lengths of transmission lines [13]

$$\gamma = \frac{\ln\left(\frac{T_{11}^{\text{ij}}+T_{22}^{\text{ij}}\pm\sqrt{(T_{11}^{\text{ij}}-T_{22}^{\text{ij}})^2+4T_{12}^{\text{ij}}T_{21}^{\text{ij}}}}{2}\right)}{l_i - l_j} \qquad (5)$$

where l_i and l_j are the lengths of two different transmission lines

$$T^{\text{ij}} = T^j(T^i)^{-1} \qquad (6)$$

and

$$T^i = \frac{1}{S_{21_i}}\begin{pmatrix} (S_{12_i}S_{21_i} - S_{11_i}S_{22_i}) & S_{11_i} \\ -S_{22_i} & 1 \end{pmatrix} \qquad (7)$$

where T^i is calculated from the measured scattering parameters.

The thickness of the thin dielectric film is made much smaller than the wavelength of the highest measurement frequency so the waveguide supports only the first TM mode. From the measured scattering parameters, the propagation constant is calculated. From the guiding condition for five-layer planar model, an effective permittivity ε_{eff} for layer 3 is numerically calculated using the Muller's complex root finding algorithm. We account for the finite width (40 μm) of the transmission line by viewing the measured $\Re e(\varepsilon_{\text{eff}})$ as the effective dielectric constant of the structure. A conformal mapping analysis of infinitely thin microstrip lines, which accounts for the end-field effects, is then used to calculate the corresponding dielectric constant $\Re e(\varepsilon_{\text{film}})$. We have found that for the structures of interest, accounting for the end effect in this manner introduces a 5% correction in the reported dielectric constant. The $\Im m(\varepsilon_{\text{eff}})$ is less sensitive to end effects and therefore is equated to $\Im m(\varepsilon_{\text{film}})$.

III. Results

Test wafers, each with 12 parallel-plate thin-film transmission lines, were implemented using standard lithographic and microfabrication techniques. A test wafer consisted of two identical sets of transmission lines with six different lengths, the longest being 29 mm, while the shortest line was 2 mm. The width of the top and bottom plate was 1000 and 40 μm, respectively. The contact pads for top plate and microwave probes were 250 $\times$ 500μm^2, and the distance between contact

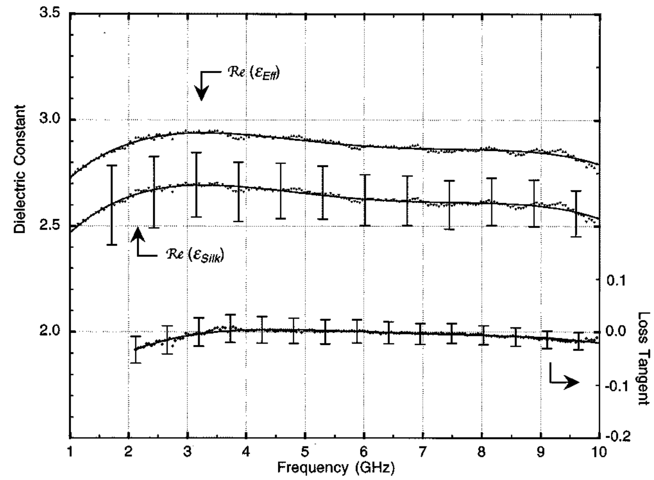

Fig. 1. Dielectric constant $\Re e(\varepsilon_{\text{SiLK}})$ and dielectric loss tangent, $\text{Im}(\varepsilon_{\text{SiLK}})/\Re e(\varepsilon_{\text{SiLK}})$ of SiLK thin films. The effective dielectric constant $\Re e(\varepsilon_{\text{eff}})$ obtained by parallel-plate analysis is also shown. The solid line is a polynomial fit to the experimental data.

pads was 750 μm from center to center. The metal layers 2 and 4 (Fig. 1) were thermally evaporated aluminum. Test wafers were made both on fused quartz and on glass (Corning precleaned microscope slide). The measurement technique is relatively insensitive to the properties of the substrate because of the shielding effect of metal layer 2. As a precautionary measure to ensure that the most uniform films can be deposited with spincoating, a planar surface was created by depositing the metal layer 2 into a 40-μm-wide trench etched into the substrate surface to a depth that equals the thickness of the deposited metal film. The channels were etched into the substrates using buffered oxide etch. The thickness of the bottom aluminum layer was controlled precisely during e-beam deposition. The low-dielectric constant material was the spincoated onto this metal layer. For the reported measurements, we have used a polyarylene low-k dielectric material (SiLK available from Dow Chemical Company). SiLK, as supplied, is a partially polymerized solution of oligomers in a mixture of cyclohexanone/butyrolactone with high-purity NMP as the carrier solvent. After the deposition of the top aluminum layer, contacts to the bottom electrode were exposed using standard microfabrication procedures. The thin-film and conductor lines' thickness measurements were made with a DEKTAK profilometer. The conductor lines' thicknesses were $d_4 = 1.54 \pm 0.03$ μm and $d_2 = 1.66 \pm 0.03$ μm. The thickness of SiLK, d_3, was 0.91 ± 0.05 μm. Conductivities of top and bottom aluminum plates were derived from measurements of dc resistance and metal geometries to be (2.32 $\pm$ 0.15) $\times$ 10^7 S/m and (2.37 $\pm$ 0.15) $\times$ 10^7S/m, respectively. The dielectric constant of the glass substrate was measured to be 6.82. The microwave properties of the structures were measured with a vector network analyzer (HP 8510B) and a microwave probe station (Cascade Probe Station) with Cascade Air Coplanar probes (ACP40-GSG). The complex propagation constant of the transmission lines was calculated using (5) at 200 different frequency points from 1 to 10 GHz. The complex permittivity was then calculated from the complex propagation constant at each measurement point as previously discussed. Within the experimental error, the dielectric measurements made on fused quartz and glass substrates were identical.

The dielectric constant and dielectric loss tangent of SiLK measured on the glass test wafer are shown in Fig. 1. The correction made to account for finite width of the waveguide can be seen from the $\Re e(\varepsilon_{\text{eff}})$ that is also shown on the figure. The dielectric constant at 10 GHz is $\varepsilon = 2.66 \pm 0.11$, and the dispersion between the high-frequency value ($f = 10$ GHz) and the low-frequency value ($f = 2$ GHz) is less than 4%. The measured ε agrees well with the published low-frequency value of $\varepsilon = 2.65 \pm 0.02$ of SiLK [14]. The dielectric loss tangent is within the bound of 3% in the frequency range 2–10 GHz, indicating that SiLK is low-loss material at microwave frequencies.

The accuracy of the dielectric constant is determined by the measurements of the propagation constant, the thin-film and metal thicknesses, and the metal conductivity. The accuracy of the propagation constant measurements is limited by the length difference between various transmission lines and random errors in the scattering parameter measurements. The probe contact pads were designed to ensure the probe placement within 10-μm precision. The multiline TRL calibration algorithm [15] and measurements made on 12 of the transmission lines were used to minimize the random errors. In calculating the permittivity from the propagation constant, the largest error occurs at the low frequencies ($f < 2$ GHz). This is due to the fact that the skin depth is larger than the metal thicknesses and inaccuracy in the metal property dominates. At high frequency, since the metal skin depth is smaller than the metal thickness, the error is dominated by the variation of the thin dielectric film thickness along each transmission line. In the test structures, these variations caused the maximum error in the dielectric constant to be 7% at 1 GHz and 4% at 10 GHz. The frequency-dependent loss characteristics of the structure are quantified by $\Re e(\gamma)$, which is influenced by the conductor loss, the geometry of the structure, and the dielectric loss. At large frequencies, the conductor loss is the dominant loss effect, and at low frequency, in this thin-film transmission-line structure, the geometrical effects dominate. At low frequency, the thickness of the conducting layers and dielectric layer is small relative to the wavelength. In the thin-film transmission-line test structure, the dielectric layer is so thin that the coupling occurs between the fields propagating in the two conducting layers, resulting in an increased propagation loss at low frequencies. This effect is so dominant that we report the loss tangent only at frequencies higher than 2 GHz.

IV. Conclusion

We presented a characterization method to determine the dielectric properties of thin low-dielectric constant films in the microwave regime. A parallel-plate thin-film transmission line geometry is used that allows rigorous electromagnetic modeling with a simple electromagnetic theory over the broad microwave frequency range. The sensitivity to thin-film properties is increased by confining the electric fields in the dielectric region. The test structures were fabricated with well-established microfabrication techniques. Compared to other dielectric measurement techniques, the method offers the advantage of greater sensitivity to thin-film dielectric properties without any system calibration or any calibrated reference. Using frequency-domain scattering parameter measurements to determine the complex propagation constant and a precise electromagnetic model to relate the propagation constant of the transmission line to dielectric permittivity of the thin film, we have measured the dielectric constant and loss tangent of a low-dielectric polymer film to better than 4% at 10 GHz.

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