Extraction of Glass-Wafers Electrical Properties Based on S-Parameters Measurements of Coplanar Waveguides

P. M. Mendes, A. Polyakov*, M. Bartek*, J. N. Burghartz*, J. H. Correia

*ECTM/DIMES, Delft University of Technology, The Netherlands

Dept. of Industrial Electronics, University of Minho, Portugal

Phone: +351 253510190, Fax: +351 253510189

E-mail: paulo.mendes@dei.uminho.pt

Abstract

The measured S-parameters of a coplanar waveguide (CPW) propagating the dominant mode were used to obtain the electrical permittivity and the dielectric loss tangent of three different glass wafers: non-alkaline Schott AF45, Corning Pyrex #7740 and Hoya SD-2. These properties were obtained up to 10 GHz. The obtained values were used together with the CPW model in ADS to obtain the simulated S-parameters for the used CPW cell. The obtained results shows good agreement between simulated and measured data.

I. INTRODUCTION

Application of wafer-level chip-scale packaging (WLCSP) techniques like adhesive wafer bonding and through-wafer electrical via formation, combined with the selected radio frequency (RF) structures allows a new level of on-chip integration [1, 2]. However, these new techniques require the combination of new materials with the standard materials used for integrated circuits fabrication. In this way, together with substrate processability, the knowledge of accurate electrical parameters is of extreme importance when designing for RF or microwave applications.

Several different methods can be used to extract the electrical intrinsic properties of a material [3]. From the most widely used techniques to obtain these properties in the microwave region, the transmission line technique is the simplest method for electromagnetic characterization in wideband frequencies [4]. The S-parameters measurements of a planar test cell can be used to obtain the desired parameters, where either microstrip or CPW can be used as test cell [5].

In this work, the coplanar waveguide (CPW) was used, with its parameters chosen to allow only the dominant quasi-TEM mode to be present. When propagating the dominant mode, the coplanar characteristic impedance is quasi-constant in a broad frequency range. Also, for on-wafer measurements the CPW, without bottom ground, is the easiest structure to feed and the probe station tips are able to touch directly the CPW lines. The S-parameters are then easily measured with a vector network analyzer.

In this paper we describe the procedure used to obtain the electrical permittivity of three different glass wafers suitable for RF-WLCSP: non-alkaline Schott AF45, Corning Pyrex #7740 and Hoya SD-2. The formulation used to obtain the values from the measured S-parameters of a coplanar waveguide test-cell is presented. The CPW test cells and the measurements steps are described. Finally, we present the results when the extracted data is used together with the ADS simulator built-in model of a CPW to design the test cell.

II. MEASUREMENT TECHNIQUE

We will now proceed with the description of the adopted method used to obtain the electrical properties of the materials under analysis.

A. Extraction method

Several methods exist to obtain the electrical properties of a material. From all of them, we have chosen one that can be used to characterize thin planar materials without any special sample requirements. The electrical properties were obtained from the S-parameters measurements of a planar transmission line test-cell. The coplanar waveguide was used because of the possibility to define a planar shape that can propagate a dominant mode (quasi-TEM). In the case of dominant mode, the coplanar characteristic impedance is quasi-constant in a broad frequency range, for a large variety of substrates and a cell structure obeying $h > W + 2S$ [1]. This cell has also the benefit of avoiding the use of vias to ground.

We will now describe the theoretical aspects of the method used to obtain the substrate properties for the different types of glass. The CPW cell geometry used for S-parameter measurements is shown in Fig. 1.

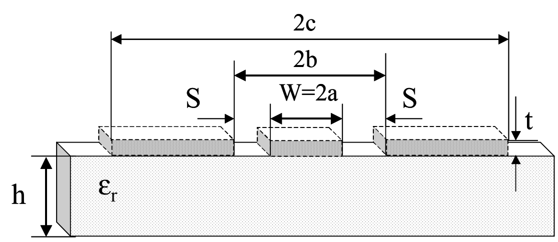

Figure 1 - CPW cell used for S-parameters measurement.

The effective dielectric constant for this type of CPW can be obtained from [5-6]:

$$\varepsilon_{reff} = -\left(\frac{-\ln T}{\omega d\sqrt{\varepsilon_0 \mu_0}}\right)^2 \qquad (1)$$

where ω is the angular frequency, ε_0 and μ_0 are the free space permittivity and permeability, d is the coplanar line length and T is the first transmission coefficient. The transmission coefficient can be obtained from the measured scattering parameters using the following equation [7]:

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{2}$$

with

$$\Gamma = \mathrm{X} \pm \sqrt{\mathrm{X}^2 - 1} \tag{3}$$

and

$$\mathrm{X} = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{4}$$

The electrical permittivity is obtained from the equations characterizing a coplanar waveguide with finite-width ground planes [8]. In this way, the effective electrical permittivity is given by:

$$\varepsilon_{eff} = 1 + \frac{1}{2}(\varepsilon_r - 1)\frac{K(k)}{K(k')}\frac{K(k_1')}{K(k_1)} \tag{5}$$

where ε_r is the relative permittivity of the substrate, K is the complete elliptical integral of the first kind and $k' = \sqrt{1-k^2}$ [9]. The arguments k and k' are dependent on the line geometry and are given by [10]:

$$k = \frac{c}{b}\sqrt{\frac{b^2 - a^2}{c^2 - a^2}} \tag{6}$$

and

$$k_1 = \frac{\sinh(\pi c/2h)}{\sinh(\pi b/2h)}\sqrt{\frac{\sinh^2(\pi b/2h) - \sinh^2(\pi a/2h)}{\sinh^2(\pi c/2h) - \sinh^2(\pi a/2h)}} \tag{7}$$

The characteristic impedance of the coplanar cell can also be computed from the measured S-parameters [11]:

$$Z_c^2 = Z_0^2 \frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2} \tag{8}$$

where Z_0 is the reference impedance (50 Ω).

To compute the attenuation, its necessary to obtain the propagation constant $\gamma = \alpha + j\beta$ for the CPW cell. This can be computed by means of [11]:

$$e^{-\gamma l} = \left\{\frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}} \pm K\right\}^{-1} \tag{9}$$

where

$$K = \left\{\frac{(S_{11}^2 - S_{21}^2 + 1)^2 - (2S_{11}^2)^2}{(2S_{21}^2)^2}\right\}^{\frac{1}{2}} \tag{10}$$

Attenuation in microwave lines occurs due to radiation, metal and substrate losses. Assuming that radiation losses are very small, it's possible to obtain the dielectric loss tangent from the value of the total attenuation and conductor losses.

The attenuation due to conductor losses in the center strip conductor and ground planes of a CPW is given by [12]:

$$\alpha_c \approx \frac{R_{sm} b^2}{16 Z_0 K^2(k)(b^2 - a^2)} \cdot \left\{\frac{1}{a}\ln\left(\frac{2a}{\Delta}\frac{(b-a)}{(b+a)}\right) + \frac{1}{b}\ln\left(\frac{2b}{\Delta}\frac{(b-a)}{(b+a)}\right)\right\} \tag{11}$$

with

$$R_{sm} = \omega\mu_c t \,\mathrm{Im}\left(\frac{\cot(k_c t) + \csc(k_c t)}{k_c t}\right) \tag{12}$$

where k_c is the wave number, ω the angular frequency and μ_c the permeability of the conductor.

From the knowledge of the total and metal losses we can obtain the dielectric loss tangent from the attenuation constant due to the dielectric losses [8]:

$$\alpha_d = \frac{\pi}{\lambda_0}\frac{\varepsilon_r}{\sqrt{\varepsilon_{eff}}} q \tan\delta \tag{13}$$

where q is the filling factor that depends on the geometry.

Next, the description of the test cells used to measure the S-parameters is presented.

B. CPW Cells Design

As referred before, the extraction method is based on the S-parameter measurements of a CPW. Several CPWs with different *W/S* ratios (W - signal line widh, S - separation of ground lines) and lengths were designed in order to provide different characteristic impedances and to allow the validation of all extracted parameters. Because the substrate losses are relatively small, lines with 5-mm length were used to increase the calculations accuracy.

All the CPW cells were fabricated on the three different glass substrates. The metal areas were fabricated with a 2 µm layer of aluminium on top of each wafer. A sample of the fabricated lines is shown in Fig. 2. Since the exact electrical permittivity value at the desired frequencies was not known, several CPW cells were designed in order to obtain a suitable configuration for the material properties extraction. It is recommended the use of some mismatch in order to obtain a good accuracy [6]. In this way, the CPW cells were designed with different *W/S* ratios in order to obtain different characteristic impedances. Namely, lines with the following dimensions were used: (*W* = 75 µm, *S* = 15 µm), (*W* = 50 µm, *S* = 35 µm), (*W* = 75 µm, *S* = 50 µm) and (*W* = 100 µm, *S* = 60 µm).

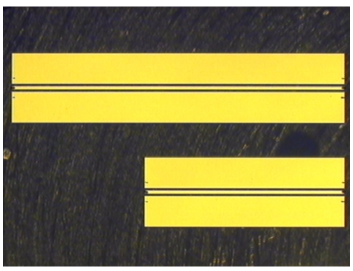

Figure 2 – Sample of the fabricated coplanar waveguides used for S-parameter measurement.

III. MEASUREMENTS AND RESULTS

A vector network analyzer and a probe station were used to perform the on-wafer measurements of the two-port network S-parameters. It was calibrated by means of TRL method, providing a measuring reference plane at the edge of the coplanar lines.

The accuracy of the obtained values depends significantly on the accuracy of the measured S-parameters [13]. In this way, the measured S-parameters of all the designed CPW cells had to be checked for accuracy and reliability. So, the same cells were measured more than once and the measured values not matching from one measurement to another were discarded. Also, four different line lengths (0.5 mm, 1 mm, 3 mm, 5 mm) were used for the same *W/S* ratio. In this way, the calculated characteristic impedance inside the same group of coplanar lines was also checked to verify the correctness of the measured values. Because the substrate losses are relatively small, lines with 5 mm length were used to improve the accuracy of its calculation.

After discarding the inaccurate data, the electrical permittivity was obtained. Fig. 3 shows the results obtained from the three wafers under analysis. As can be seen from that figure, for high frequencies, and as expected, the electrical properties show only a slight variation with frequency. Also, we can observe an abrupt change on the measured characteristics at low frequencies. This happens because at those frequencies the assumptions behind the theoretical formulation are not anymore valid. At the frequencies of interest (5-6 GHz), the dielectric constants for SD-2, borofloat and AF45 are 4.7, 5.9 and 6.1, respectively.

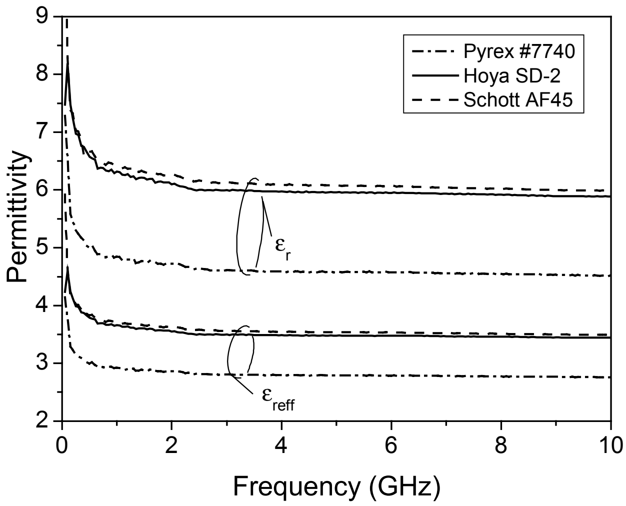

Figure 3 – Measured permittivity.

The measured data was used to compute the characteristic impedance of the CPW cells, used to validate the measured S-parameters. Fig. 4 shows the input impedance values obtained for a CPW cell on different substrates.

The losses are difficult to obtain since they are relatively small for such line lengths. The results can change significantly from one measurement to another, if not enough attention is paid when the contact between probes and lines is established. To compute loss values, the remaining data after discarding the inaccurate measurements were again submitted to a new selection. Only the ones giving the lower values for the losses were used. It was considered that the higher losses were due to imperfect contacts between probes and CPW cells.

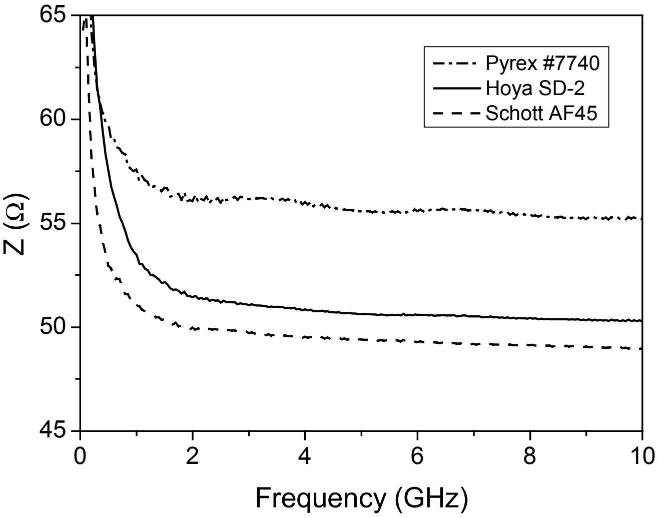

Figure 4 – Measured characteristic impedance of the CPW cell with $W = 75$ µm and $S = 15$ µm.

In Fig. 5, the total attenuation measured in a CPW cell is plotted together with the attenuation due to conductor loss, computed from (11). Assuming the radiation losses being very small, the difference between total losses and conductor losses give us the substrate losses.

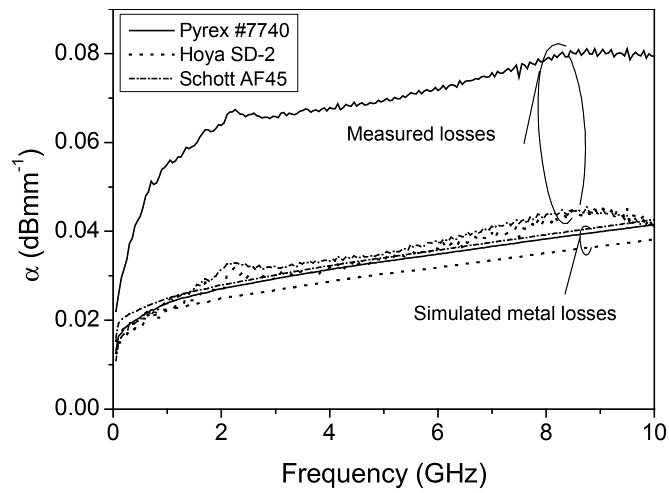

Figure 5 – Computed and measured attenuation of a CPW cell with $W = 75$ µm and $S = 50$ µm.

From the above figure we can see that the SD-2 and AF45 substrates suffer from almost the same losses, but the #7740 substrate suffer from increased losses. When designing RF and microwave elements, the structures on the Pyrex and AF-45 wafers should be similar but not the device losses.

The data from Fig. 5, together with (13) and data from Table I in [12] was used to compute the loss tangents. The obtained results are plotted in Fig. 6. As expected from total losses, the SD-2 and AF45 wafers show similar values, and

Pyrex wafer presents a higher value for the loss tangent. When possible, AF45 should be used instead of Pyrex #7740.

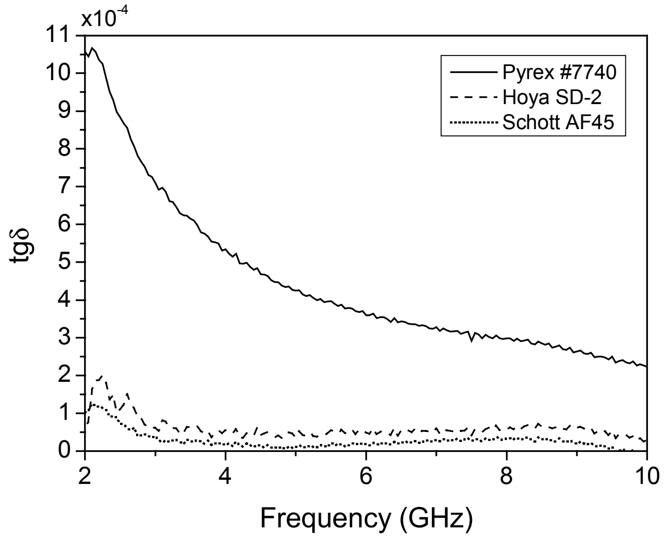

Figure 6 – Measured loss tangent (*W*=75 μm, *S*=50 μm).

Next we present the simulation done using the previous extracted parameters into ADS simulator CPW model.

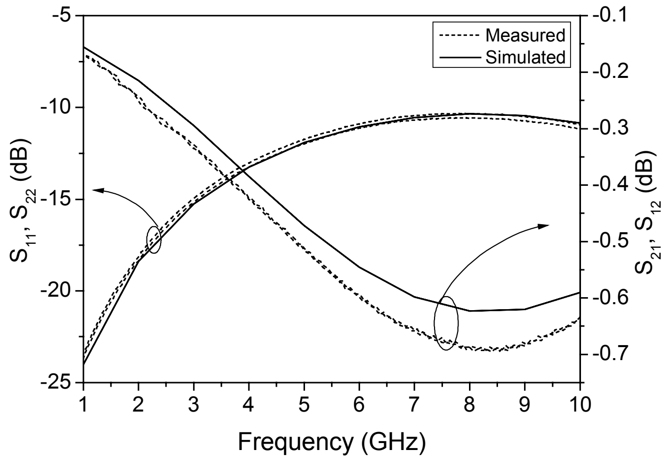

Figure 7 – Measured and simulated S-parameters of a CPW.

We can see that the simulated results are in good agreement with the measured ones. These final results allow us to support the validity of the extracted parameters.

IV. CONCLUSIONS

In this work, the electrical properties of three different glass wafers suitable for RF-WLCSP were investigated. First the characteristic impedance and losses of the CPW lines were determined. Then, the electrical permittivity and the loss tangent were obtained. These properties were obtained up to 10 GHz. It was verified that the AF45 wafer has the highest dielectric constant and the SD-2 wafer the lowest. It was also found that the Pyrex #7740 wafer presents the highest losses when compared with the other two types of glass wafers investigated. Finally, the usefulness of the obtained values was checked trough a simulation done with a built-in model of ADS.

ACKNOWLEDGEMENTS

The authors would like to thanks the Portuguese Foundation for Science and Technology for funding this project (POCTI / ESE / 38468 / 2001).

REFERENCES

[1] P. M. Mendes, A. Polyakov, M. Bartek, J. N. Burghartz, J. H. Correia, "Integrated 5.7 GHz Chip-Size Antenna for Wireless Sensor Networks", to appear in Transducers'03, Boston, USA, June 8-12, 2003.

[2] A. Polyakov, P.M. Mendes, S.M. Sinaga, M. Bartek, B. Rejaei, J.H. Correia, J.N. Burghartz, "Processability and Electrical Characteristics of Glass Substrates for RF Wafer-Level Chip-Scale Packages", to appear in ECTC 2003, New Orleans, USA, May 27-30, 2003.

[3] Hewlett Packard, "Basics of measuring the dielectric properties of materials", Application Note 1217-1.

[4] Juan Hinojosa, "S-Parameter Broadband Measurements On-Coplanar and Fast Extraction of the Substrate Intrinsic Properties", IEEE Microwave and Wireless Comp. Letters, Vol. 11, nº 2, pp. 80-82, Feb. 2001.

[5] Juan Hinojosa, K. Lmimouni, G. Dambrine, "Fast Electromagnetic Characterization Method of Thin Planar Materials Using Coplanar Line up to V-band", Electron. Lett., Vol. 38, nº 8, pp. 373-374, April 2002.

[6] Juan Hinojosa Jimenez, "Contribuition a l'Elaboration d'une Nouvelle Methode de Caracterisation Electromagnetique de Materiaux a Partir de Lignes Plaquees – Applications a l'Etude de Nouveaux Materiaux", Universite des Sciences et Technologie de Lille, Lille, France, These a Docteur de l'Universite, May 1995.

[7] Abdel-Hakim Boughriet, Christian Legrand, Alain Chapoton, "Noniterative Stable Transmission/Reflection Method for Low-Loss Material Complex Permittivity Determination", IEEE Trans. Microwave Theory Tech., Vol. 45, nº 1, pp. 52-56, January 1997.

[8] Rainee N. Simons, *Coplanar Waveguide Circuits, Components and Systems*, John Wiley & Sons, 2001.

[9] Robert E. Collin, *Foundations for Microwave Engineering*, 2nd edition, McGraw-Hill, 1992.

[10] C. Veyres, V. F. Hanna, "Extension of the Application of conformal Mapping Techniques to Coplanar Lines with Finite Dimensions", Int. J. Electron., Vol.48, nº. 1, Jan. 1980.

[11] William R. Eisenstadt, Yungseon Eo, "S-Parameter-Based IC Interconnect Transmission Line Characterization", IEEE Trans. Components, Hybrids, and Manufact. Techn., Vol. 15, nº 4, pp. 483-489, August 1992.

[12] C. L. Holloway, E. F. Kuester, "A Quasi-Closed Form Expression for the Conductor Loss of CPW Lines, with an Investigation of Edge Shape Effects", IEEE Trans. Microwave Theory Tech., Vol. 43, nº 12, pp. 2695-2701, December 1995.

[13] Yi-Chi Shih, "Broadband Characterization of Conductor-Backed Coplanar Waveguide Using Accurate On-Wafer Measurement Techniques", Microwave Journal, Vol. 34, nº 4, pp. 95-105, April 1991.