Membrane Probe Technology for Non-destructive Thin-Film Material Characterization

A. Pham, A. Mathis, J. Laskar, A. F. Peterson and L. Hayden*

Packaging Research Center
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250

*Cascade Microtech, Inc.
14255 SW Brigadoon Ct.
Beaverton, OR 97005

Abstract

We present the design and development of the membrane probe prototype for non-destructive characterization of thin-film materials [1]. This material membrane probe (MMP) is designed with multiple polyimide coplanar wave guide transmission lines (CPW), which enable effective and accurate on-wafer Thru-Reflect-Line [2] calibration. This MMP significantly improves upon the calibration integrity and measurements over previous results [1]. We have measured dielectric properties of various materials at microwave frequencies and conclusively demonstrate that the MMP can be used to non-destructively characterize thin-film materials.

I. Introduction

Technological advances in high density microwave packaging will require the use of multi-layer dielectric substrates. Accurate characterization of dielectric properties is a critical step for successful and effective microwave designs. To address this critical design step, we have designed the MMP for non-destructive material characterization. The gaps of the CPW can be varied to allow

different field penetration into an MUT. This characteristic enables the probe to measure substrates with thickness less than 2 mils non-destructively.

In this paper, we present the design, analysis and measurements of the second generation MMP using the commercial Pyramid® probe process from Cascade Microtech, Inc [3]. We have incorporated a set of TRL standards into the probe to enable accurate calibration. This calibration allows us to accurately measure the S-parameters of the built-in multi-layer CPW lines without de-embedding transitions and connectors [1]. The dielectric properties of materials are then determined from the measured S-parameters of the multi-layer CPW lines. Dielectric properties of InP, fused quartz and alumina have been characterized to demonstrate the feasibility of this technique to 4 GHz. We have developed an electromagnetic model to relate the measured effective permittivity to the relative dielectric constant.

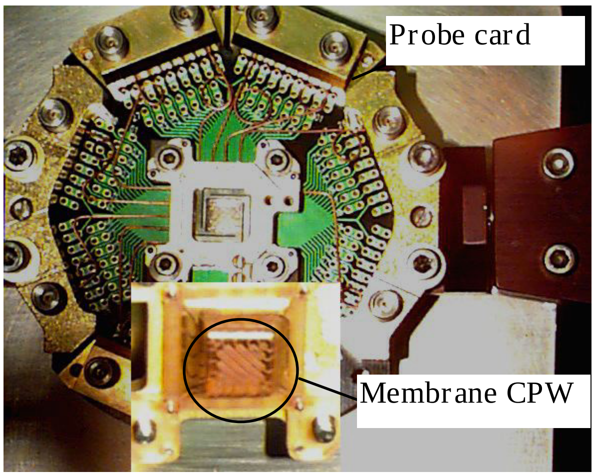

Figure 1. Prototype of the membrane core and a probe card

II. Design concept of the membrane probe

We have designed the MMP using membrane coplanar waveguide transmission lines as interfaces to an MUT. These CPW lines are fabricated and incorporated into a core mounted on a probe card. This probe card provides coaxial connectors for input signals. In Figure 1, we illustrate the prototype of a core and a probe card set-up for measurements. The cross-section of a membrane CPW line is shown in Figure 2. The flexible polyimide layers ensure intimate contact between the MMP and an MUT. The bottom layer of the MMP protects the metalization for repeatable contacts of different substrates.

To measure an MUT, we impress the MMP on a bare thin-film material substrate. The MUT is considered as a part of the multi-layer CPW and serves as a third dielectric layer. In Figure 3, we show the schematic cross-section of the MMP impressed upon a substrate. The objective of this technique is to experimentally obtain S-parameters of the multi-layer CPW lines. We can then extract the dielectric properties of the MUT from measured S-parameters of this CPW line.

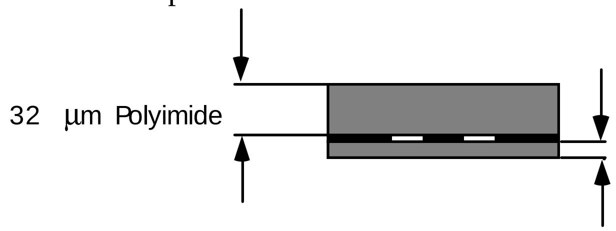

Figure 2. A cross-section of the membrane CPW transmission line

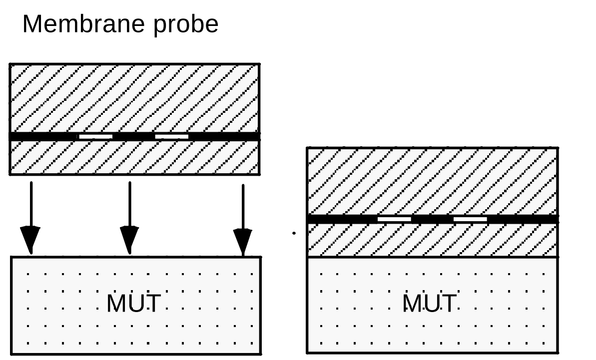

Figure 3. A cross-section of the membrane CPW on a material substrate under test

III. Calibration Approach

We employ the Thru-Reflect-Line (TRL) calibration technique [3] to define measurement reference planes at the membrane CPW lines. The multi-layer CPW calibration standards have two polyimide and one alumina dielectric layers as shown in Figure 3. We have designed a set of TRL calibration standards with this cross section using an EM solver implemented by the Method of Moments.

The MMP itself has CPW lines with two layers of polyimide as shown in Figure 1. The designed CPW calibration standards have three dielectric layers as shown in Figure 3. We perform TRL calibrations by impressing the MMP on an alumina substrate. This forms CPW line calibration standards, which have two polyimide and one alumina dielectric layers. After the calibration, we are able to set the measurement reference planes at the membrane CPW so that only S-parameters of the multi-layer CPW lines are collected [4,5].

IV. Experimental Results

We have measured the S-parameters of InP, fused quartz, and alumina using the MMP. Figure 5 shows the measured phases determined from S_{21} for these substrates. The phases of S_{21} are substantially different among materials with various dielectric constants. These distinctions indicate that the MMP differentiates very well the dielectric properties of different materials.

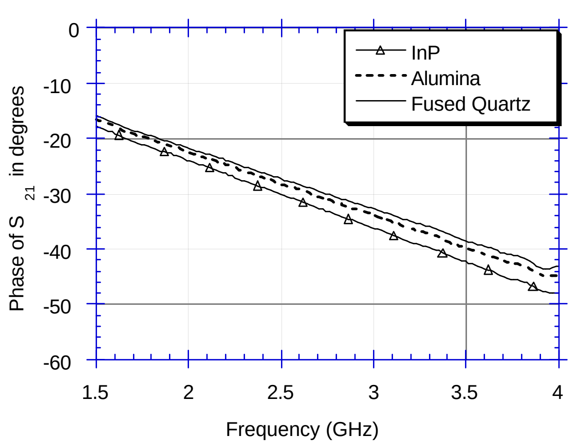

Figure 4. Phase of S_{21} of InP, fused quartz and Kapton

The ABCD matrix of a transmission line is defined [6]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_{ol}\sinh(\gamma l) \\ \dfrac{\sinh(\gamma l)}{Z_{ol}} & \cosh(\gamma l) \end{bmatrix} \quad (1)$$

where Z_{ol} and γ are the characteristic impedance and the propagation constant of the multi-layer CPW line. The measured S-parameters can be transformed to ABCD parameters . Therefore, the propagation constants can be determined:

$$\gamma = \frac{1}{l}\cosh^{-1}(A) = \frac{1}{l}\ln\left(A \pm \sqrt{A^2 - 1}\right) \quad (2)$$

where l is the length of the transmission line. The effective permittivities of the multi-layer CPW lines are calculated from the measured propagation constants given by (2). Figure 6 shows the measured effective permittivities of InP, fused quartz, and alumina multi-layer CPW lines to 4 GHz.

In order to determine the relative permittivity of the substrate, an integral equation is formulated for the electric field in the apertures. This is then discretized using the spectral domain method [7] to generate an admittance matrix. Traditionally one solves the nonlinear eigenvalue problem for the propagation constant. Here, we fix the propagation constant and find the substrate permittivity where the determinant of the admittance matrix vanishes. This allows us to directly solve for the substrate permittivity given the propagation constant. Table 1 shows the relative permittivities of alumina, fused quartz, and InP from 1.5 to 4 Ghz. Within this bandwidth, the relative permittivities have a maximum variation of +/- 8.00% [8].

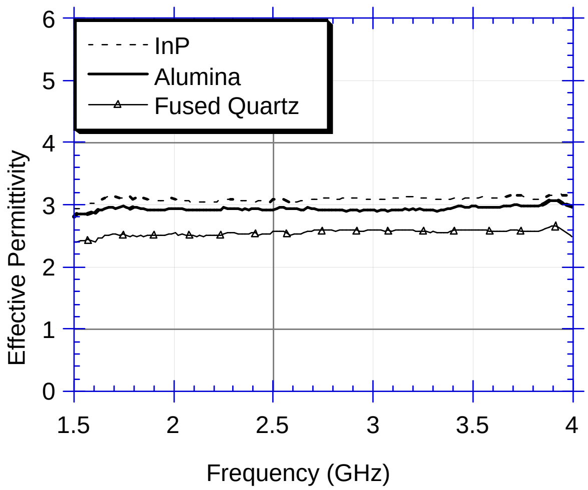

Figure 5. Measured effective permittivity of InP, fused quartz, and alumina

Table 1. Measured relative dielectric constants

	Alumina	InP	Fused Quartz
ε_r	9.2	12.4	3.8

IV. Conclusion

We have designed and developed the MMP to non-destructively characterize thin-film materials. We successfully develop an effective TRL calibration technique for this probe. We demonstrate that this probe can measure dielectric properties of thin-film materials to 4 Ghz. The initial results reported here demonstrate that the MMP has sufficient sensitivity to characterize various thin-film structures. We also develop a numerical EM technique to calculate the relative permittivity from the effective one of the multi-layer CPW line. We demonstrate the dielectric constant measurements of InP, fused quartz, and alumina.

Acknowledgment

The authors would like to acknowledge the support of the NSF Packaging Research Center at Georgia Tech under contract ECE-9402723 and NSF career award under contract ECS-9623964.

References

[1] E. Seltmann, J. Laskar, K. Smith, "Development of a coplanar waveguide membrane probe for non-destructive evaluation of thin film structures", IEEE MTT-S, pp. 1411-1415, vol. 3, 1996

[2] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," IEEE Transactions on Microwave Theory and Techniques, pp. 1205-1215, July 1991

[3] Cascade Microtech, Inc., 14255 SW Brigadoon Ct., Beaverton, OR 97005.

[4] DEEMBED software, National Institute of Standards and Technology

[5] R. B. Marks and D.F Williams, "Characteristic Impedance Determination using Propagation Constant Measurement," IEEE Microwave and Guided Wave Letters 1, pp. 141-143, June 1991 -81, Dec. 1991

[6] K. Kiziloglu et al, "Experimental Analysis of Transmission Line Parameters in High-Speed GaAs Digital Circuit Interconnects," IEEE Transactions on Microwave Theory and Techniques, pp. 1361-1367, Aug. 1991

[7] T. Uwaro and T. Itoh, "Spectral Domain Approach" in Numerical Techniques for Microwave and Millimeter-Wave Passive Structures, T. Itoh, ed., John Wiley & Sons, New York, 1989.

[8] Dielectric Materials Measurements, Solutions Catalog of Fixtures & Software Hewlett-Packard Company, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403

0-7803-4471-5/98/$10.00 (c) 1998 IEEE