Conductor Backed Thin Films Non-Destructive Dielectric Characterization using Coplanar line

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***Abstract*—This paper introduces a new and simple method to determine the relative permittivity of thin film materials deposited on metallic substrate. The method is a non-destructive one, and uses the conformal mapping technique to extract the relative permittivity and loss tangent by applying an inverse problem after measuring the S-parameters of the material when placed on a coplanar transmission line. The obtained results are satisfying and the method is validated using standard FEM simulation software. The permittivity measurement can be done down to a thin film of 5 micrometer thickness.**

Keywords—Permittivity, Dielectric Constant, Thin Films, Coplanar Waveguide, Conformal Mapping.

I. INTRODUCTION

The fast advance in technology these days partially returns to the smart materials and their integration in electronic devices. These materials are integrated in thin layers in the realization of controllable devices at ultra-high frequencies, thus minimizing the price, volume and losses of today's' electronic circuits.

Essential before the use of new materials in the applications, a behavioral characterization at the work frequency is required. Ferroelectric materials are a special category of dielectric materials often used as thin films in microwave electronics for developing electrically tunable microwave integrated circuits. The dielectric constant of ferroelectric materials can be varied by applying an external dc electric field. Furthermore, ferroelectric materials can be used for the development of tunable microwave devices, which have potential applications in satellite, terrestrial communications, and other microwave applications where the working frequencies are higher than the useful range of Si-based devices. Having application potentials in various fields, including miniature capacitors, electrically tunable capacitors and electrically tunable phase-shifters, a precise knowledge of the dependence of the permittivity, characteristic impedance and loss tangent of ferroelectric thin films is needed.

A non-destructive method of characterization using a CPW structure is already presented and discussed by us in [1]. Here, we give more attention to the characterization of thin films deposited directly on metallic substrate; thus opening the way to characterize materials before their integration is capacitor and at high frequencies. In addition, this will help us to compare our results at high frequencies with those of capacitive method at low frequencies.

II. CHARACTERIZATION METHOD

A. *Coplanar line (CPW)*

The theory of the method and its principle is very simple; the substrate to be measured is placed on the line for an assembly as described in Fig.1 below, where the line is taken in sandwich between 2 dielectric substrates, that of the line and the material to measure. Where the film is backed by a metallic layer.

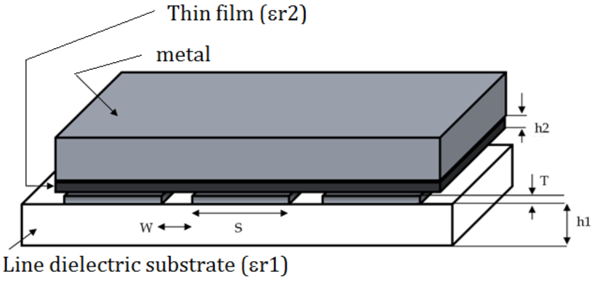

Fig. 1. Schematic Of A CPW Tight Between Two Dielectric Substrates.

The calculation is done by measuring the S-parameters of both: "the coplanar line" and the "coplanar line loaded". The phase difference of 2 measurements will help in extracting the permittivity of the loaded material and that using the conformal mapping analysis.

B. *Theory and formulation:*

The method followed for measurement of the complex permittivity of thin film material uses the transmission coefficient "S_{21}". Since, S_{21} is less affected by the random errors related to the signal/noise ratio of the network analyzer, than the reflection coefficient S_{11}, this measurement is intended to determine with a good precision the value of the propagation constant in the line incorporating the thin film.

The transmission coefficient can be expressed as $S_{21} = e^{-\gamma l}$. Where "l" is the length of the material to be measured and γ is the propagation constant of a coplanar wave guide well known as:

$$\gamma = j\frac{2\pi}{c} f\sqrt{\varepsilon_{eff}\mu_{eff}} \tag{1}$$

Where ε_{eff} is the effective permittivity of the whole system, μ_{eff} the effective permeability which is equal to '1' in the case of dielectric medium and 'f' is the frequency.

The ratio of the two measurements mentioned before gives the following formula:

$$\left.\underset{(\text{loaded})}{S_{21}}\middle/\underset{(\text{unloaded})}{S_{21}}\right. = e^{-(\gamma_c-\gamma_v)} = e^{j\frac{2\pi}{c}.f.l.(\sqrt{\varepsilon_{reff_v}}-\sqrt{\varepsilon_{reff_c}})} \qquad (2)$$

Where (γ_c), ε_{effc}, (γ_v) and ε_{effv} are propagation constant and the effective permittivity of the system with and without the load respectively.

The conformal mapping method cited in [2] is used to represent our multi-layered system. The simplified formula for a 1-layered structure (the coplanar line alone) is given by:

$$\varepsilon_{effv} = 1 + q_1 (\varepsilon_{r1} - 1) \qquad (3)$$

Where ε_{r1} is the permittivity of the coplanar line substrate and q_1 is the filling factor calculated using the elliptical integral of first kind and discussed in [3, 4].

On the other hand, the permittivity of the whole system loaded with the substrate is a little bit more complex and will be derived directly from the partial capacitors for the multilayered system.

The total capacitance C_{cpw} of the sandwiched CPW is the sum of the partial capacitances C_1, C_2, and C_{air} of the three partial regions shown below in Fig. 2:

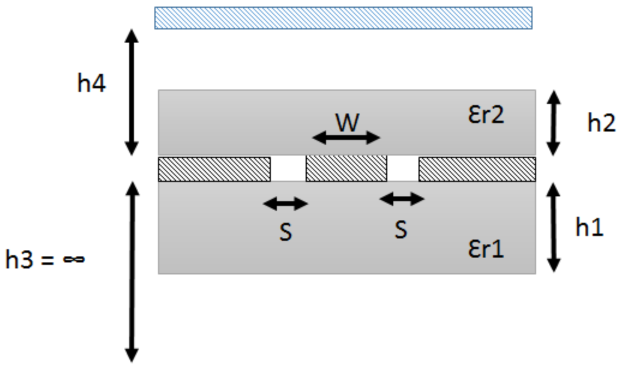

Fig. 2. Schematic of a 4 regions above and below the coplanar line.

Following the analysis depicted in [2] here we have, $h_3 = \infty$ and $h_4 = h_2$ ($k_2 = k_4$). So:

$$C_1 = 2\,\varepsilon_0(\varepsilon_{r1} - 1)\frac{K(k_1)}{K(k_1')} \qquad (4)$$

$$C_2 = 2\,\varepsilon_0\varepsilon_{r2}\frac{K(k_2)}{K(k_2')} \qquad (5)$$

And

$$C_{air} = 2\,\varepsilon_0\frac{K(k_0)}{K(k_0')} + 2\,\varepsilon_0\frac{K(k_2)}{K(k_2')} \qquad (6)$$

Where

$$k_0 = \frac{S}{S + 2W} \qquad (7)$$

$$k_1 = \frac{\sinh\left(\frac{\pi S}{4h_1}\right)}{\sinh\left[\frac{\pi(s + 2W)}{4h_1}\right]} \qquad (8)$$

And

$$k_2 = \frac{\tanh\left(\frac{\pi S}{4h_2}\right)}{\tanh\left[\frac{\pi(s + 2W)}{4h_2}\right]} \qquad (9)$$

and $K(k_i)$ is the complete elliptical integral of first kind, and $K(k_i') = K(\sqrt{1-k_i^2})$.

S and W are the CPW conductor and slot width respectively, h_1 and h_2 are the thickness of the different layers.

Summing the capacitors:

$$\Rightarrow \quad C_{cpw} = C_1 + C_2 + C_{air} \qquad (10)$$

And $$\varepsilon_{effc} = C_{cpw} / C_{air} \qquad (11)$$

Substituting ε_{effv} and ε_{effc} in the equation (2) will makes it possible to extract the complex permittivity ε_{r2} of the film. The above equations are written in a Matlab program to allow simple calculation.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Preparation and circuit characteristic*

The coplanar line employed here, was designed for a characteristic impedance of 50Ω to match the coaxial cable of the network analyzer used to measure the S-parameters. MgO substrate was taken as the line support of permittivity 9.45 and loss tangent of 0.001. The parameters for the coplanar printed on the substrate are as follows: Substrate thickness = 0.5mm, central conductor width w = 120µm, spacing between the central conductor and the ground plane s = 84µm with a metallic thickness t = 2µm.

B. *Sample specifications*

As it is the case for most measurement methods the samples are better to be machined and shaped to rectangular form. The materials must be smaller in length than the line but wide enough to cover the 2 ground planes in a way to confine the field lines. The material to be measured is placed on the line;

The thin ferroelectric films measured here are barium strontium titanate ($B_{60}S_{40}T$) deposited with thicknesses varied between 1µm and 10µm on metallic layer of pt. (platinum). The S-parameters are measured using a vector network analyzer up to 10 GHZ. The line is mounted on a classical ANRITSU test-fixture. Both transmission coefficients measured without load and loaded with material are integrated in the aforementioned program in order to extract the permittivity of the thin layer by applying the analysis described above.

C. Method validation

Before starting our measurements, the method was validated using HFSS electromagnetic simulation software. Where we measured films with different thicknesses ranging from 0.5µm to 30µm, while varying the permittivity from 50 up to 1000. The results showed a good precision for samples of 5µm and above, while the percentage error increases while decreasing the film thickness, presenting a higher relative permittivity than the real one. This returns to the fact that the reflection increases while minimizing film thickness, since the film start to look non-significant with respect to the metallic layer. A better solution could be present if a line of smaller dimensions is used.

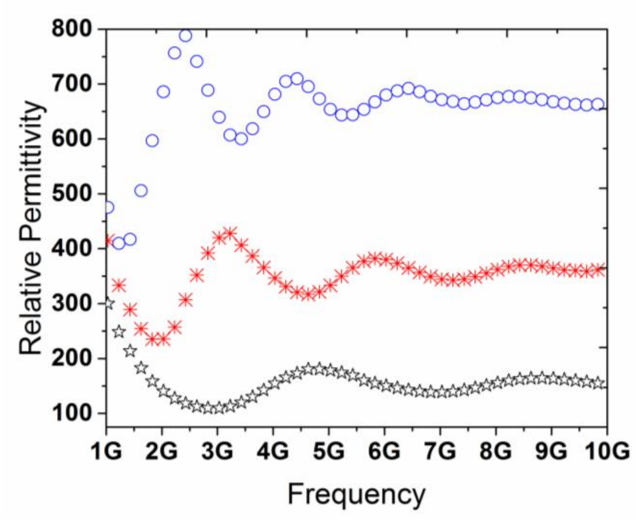

Fig. 3. Relative Permittvity of 3 different layers (simulated results).

In the figure above (Fig. 3), we present 3 different values for the permittivity chosen to be 150, 350 and 650. The simulation is done with HFSS and then the results of transmission coefficient is exported and entered to the matlab program where the permittivity is extracted.

D. Obtained measurement results

In the following we present the results obtained when a film sample of 5µm backed by a metallic substrate is placed on the coplanar line.

The plot of the transmission coefficients S_{21} loaded and unloaded (Fig. 4). We can see that transmission is very low, due to the high permittivity of the thin film in addition to the presence of the metallic substrate.

The phase angles of the tranmission coefficients for the 2 states: Loaded and unloaded and shown in Fig. 5. A high shift in the phase angle in seen when the BST film material is placed on the substrate.

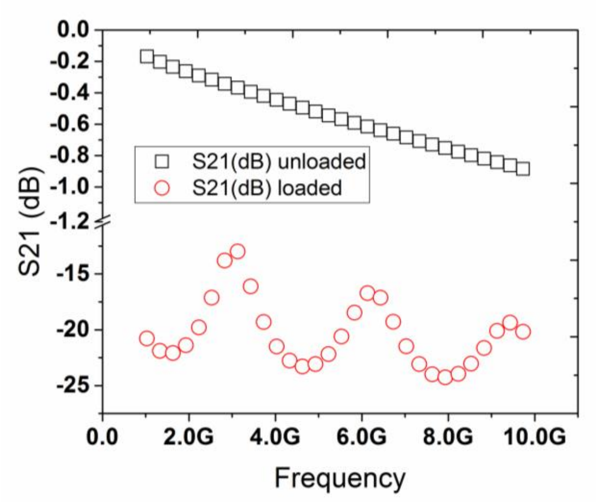

Fig. 4. The 2 transmission coefficient in dB of the 2 measurements (loaded and unloaded)

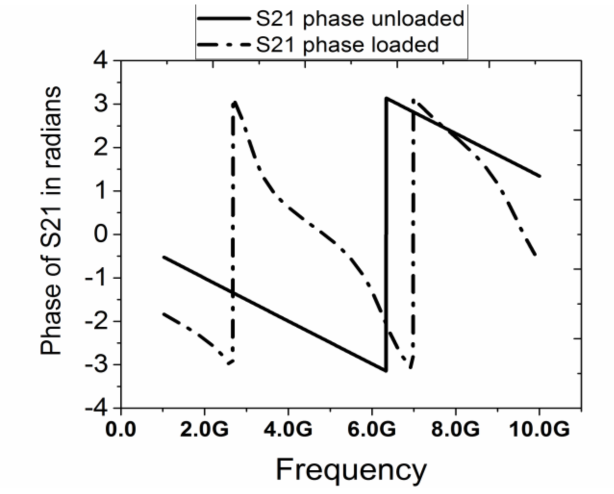

Fig. 5. The 2 phase angles of the 2 measurements (loaded and unloaded)

Finally in Fig. 6, the relative permittivity of the film is presented side by side with the value of the loss tangent obtained. The permittivity is found to around 200, a result similar to all other BST samples measured and comparable to results previously presented in [5] for that type of films. A high variation in the permittivity is appears at first and that due to the mismatch between the CPW+ sample and the network analyzer cables. The CPW is designed to have 50Ω characteristic impedance, yet when the sample is placed, the characteristic impedance will vary with the value of the thin permittivity and thickness.

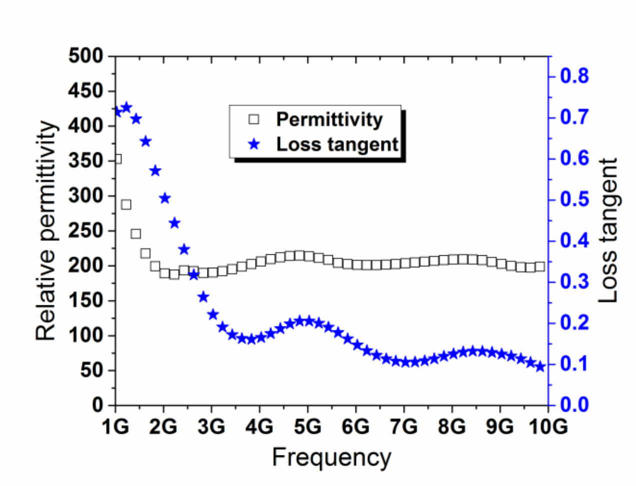

Fig. 6. Result of the relative permittivity obtained for a BST sample with the corresponding loss tangent.

The mismatch clearly appear on the loss tangent result which shows a considerably large value. This return to the fact the conductive losses due to the metallic substrate are not taken into consideration in the measurement done.

IV. ERROR ANALYSIS

The main source of error in such non-destructive methods comes from the roughness of the metallic substrate, referred usually as an air gap. Normally, an air gap will not exist since a contact is always present between the line and the thin film.

The substrate roughness could introduce some uncertainties to the permittivity measurement done. This problem is already discussed in [5] and it was found that the calculation with minimal thickness h_{min} for a substrate of thickness varying between h_{min} and h_{max}, reduces the error to 5% for 30% film roughness and for 10% roughness, the error in the permittivity value will not bypass the 3%. In conclusion, all depends on the substrate of the layer.

On the other hand, uncertainties in the loss tangent measurements are referred to the conductive losses of the film metallic substrate which should be considered.

V. CONCLUSION

Our study in this paper is directed toward the non-destructive thin films dielectric characterization using a coplanar line. The method seems of great interest for permittivity measurement.

On the other side, measurements for the loss tangent did not follow the same rule as that of the permittivity. There is indeed high percentage of error presented in the measurement done due to metallic substrate conductive loss.

The method present an advantage in that we can compare our results obtained at high frequency to those obtained with capacitive methods at low frequencies since we can do the measurement on the same samples under the same conditions of deposition. In addition to this, it will help to detect any relaxation in the materials along the large band of measurement.

Promising results are obtained, however they highlighted on the need to increase the precision of the method to measure thinner films of thicknesses of the order of 1µm and below. A solution arises probably through using a CPW with narrower slot gaps.

REFERENCES

[1] Hussein Kassem, Valérie Vigneras, Guillame Lunet, “Non destructive dielectric characterization of thin ferroletric films materials using coplanar line structure”, Integrated Ferroelectrics, 94 (01), Dec 20, 2007, pp. 82 – 93.

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

[3] Spartak S. Gevorgian, “Conformal mapping of the field and charge distributions in multi-layered substrate CPW’s”, IEEE transaction on microwave theory and technique,vol 47 No.8, August 1999.

[4] Spartak S. Gevorgian , “CAD Models for multilayered CPW ”. IEEE transaction on microwave theory and technique,vol 43 No.4, April 1995.

[5] Hussein Kassem, Valérie Vigneras, Guillaume Lunet; Electric Field effect on the permittivity of various BST composites thin films materials, Proceeding of the 40th European Microwave Conference IEEE. Paris 2010, ISBN: 978-1-4244-7232-1, pp. 1528 - 1531.