Dielectric measurement of Thin BST films materials using CPW and Microstrip lines

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ABSTRACT

This paper presents a comparison of different planar circuits dielectric measurement methods. The measurement is made on Barium Strontium Titanate ($B_{60}S_{40}T$) thin films samples of thickness of 700nm deposited on MgO and sapphire substrates. The measurements is done using 2 methods with both methods are used in transmission: «coplanar line» and «Microstrip line» and both are destructive ones. The measurement results obtained for the permittivity and the loss tangent at high frequencies till 20 GHz. Subsequently, a review of these different methods is presented.

Keywords: Permittivity, dielectric constant, thin films, coplanar waveguide, microstrip line.

1. INTRODUCTION

Ferroelectrics are a class of dielectric materials which offers unusually large values of dielectric constant that can be altered under the influence of an externally applied electric field. These materials are of great interest in the microwave range because of their electrically alterable dielectric constant which offers a changing phase shift to an EM wave passing through it. This property lures ferroelectrics as an attractive control element in various microwave applications. Ferroelectrics are generally made both in bulk ceramic form as well as in the form of thin-films. The advantage of thin-film ferroelectrics is that, only few volts of external electric field is necessary to induce sufficient change in the dielectric constant, in contrast to the bulk form, needing a few kilo-volts. Other ferroelectric materials advantages is presented also in a fast switching time, and a high permittivity allowing electronic devices miniaturization, yet the major disadvantage stays in their high dielectric losses. Despite this, recently, notable applications of thin-film ferroelectrics in microwave applications are reported.

Essential before the use of these new materials in the applications, this work is devoted to their characterization at microwave frequencies. A study of different planar destructive methods for characterization of these materials using coplanar line and microstrip line structures has been studied and tested. The future work will be devoted to the dynamic characterization of these materials; the characterization under the application of a continuous field will be made to show the variation of permittivity and thus the performance these materials in different applications.

2. CHARACTERIZATION METHODS

Our work is directed towards the study of various devices at high frequencies, and in transmission that can be later on used for the measurements under voltage application. As already been indicted, the circuits used are: in transmission: "coplanar and microstrip lines". In order to improve our structures, a number of simulations were carried out using a commercial EM software: "ANSYS HFSS".

A. Coplanar line (CPW)

The method presented is based on the use of a coplanar transmission line incorporating the thin ferroelectric layer to characterize (Fig. 1). In general the film is deposited with 0.7µm thickness on a sapphire substrate by Rf-sputtering, and the metallization (conducting strip and ground planes) are printed on the thin BST layer. In this field, one can quote for example the work described in [1, 2], which allows the determination of the permittivity of a thin layer integrated in a microstrip line. The permittivity is obtained starting from measurement of the propagation constant and the characteristic impedance of the line using a network analyzer.

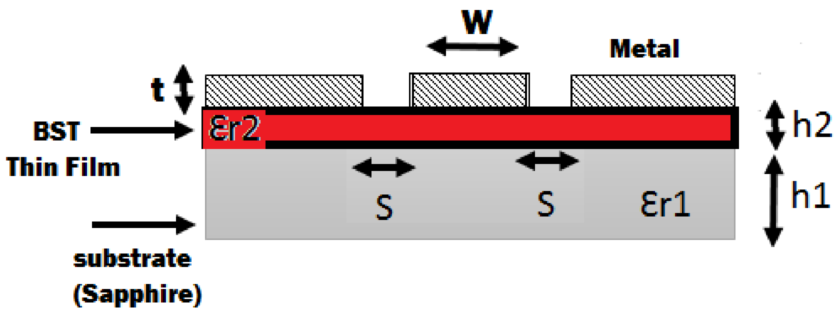


Figure 1. CPW incorporating the thin layer.

Theory and formulation:

The method followed for measurement of the complex permittivity of BST ferroelectric material uses the transmission coefficient "S_{21}". Indeed, 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}. Thus, this measurement is intended to determine with a good precision the value of the propagation constant in the line incorporating the thin film. This latter is expressed as follows:

$$\gamma = \alpha - j\beta \tag{1}$$

Where "γ" is the attenuation constants in 'dB/cm', "β" is the phase constant in 'rad/cm' of the measured line and related to S_{21} by these expressions:

$$\alpha = - S_{21\,(dB)} / L_{(cm)} \text{ and } \beta = \varphi_{21\,(rad)} / L_{(cm)}. \tag{2}$$

Where 'L' is the length between the reference planes of measurement (length of the line) and 'φ_{21}' is the phase of S_{21} in radians. The effective permittivity of the studied structure "ϵ_{eff}" can be simply extracted from the preceding relation:

$$\epsilon_{eff} = -\left(\frac{C\gamma}{2\pi f}\right)^2 \tag{3}$$

The conformal mapping method cited in [3-5] is used to represent our multi-layered system. The simplified formula for a 2-layered structure is given by:

$$\epsilon_{eff} = 1 + q_1(\epsilon_{r1} - 1) + q_2(\epsilon_{r2} - \epsilon_{r1}) \tag{4}$$

Where ε_{r1} is the permittivity of the substrate, ε_{r2} that of the thin film and q_i is the filling factor calculated from the elliptical integral of first kind. According to this equation the contribution of the thin layer to the effective permittivity of the line is directly proportional to the coefficient q_i. For i = 1, 2 …

$$q_i = \frac{1}{2}\frac{K(k_i)}{K'(k_i)}\frac{K'(k_0)}{K(k_0)} \tag{5}$$

$$k_0 = \frac{S}{S + 2W} \tag{6}$$

$$ki = \frac{\sinh\left(\Pi S / 4hi\right)}{\sinh\left(\Pi(s + 2W) / 4hi\right)} \tag{7}$$

$K_{(X)}$ is the elliptic integral of the first type and $K'(x) = K[\mathrm{sqrt}(1-x^2)]$. Knowing the various geometrical and electromagnetic parameters of the coplanar line, except the permittivity of the thin layer to characterize, the latter can be simply deduced.

B. Microstrip Line

The second method presented here, uses a microstrip line. The representation is similar to that of the coplanar line; that is, the film is incorporated in the microstrip structure (Fig. 2).

In the quasi-static analysis, one supposes that the fundamental mode of the wave propagation in a microrstrip is pure TEM. Being non-homogenous, a microstrip line is described by two parameters, the effective permittivity and the characteristic impedance Z_0, which can be obtained from the quasi-static analysis [6, 7], this for the case of 1-layer device.

The multi-layered structure is also presented in [8, 9], to extract the effective permittivity. Yet, complexity presents when inversing the problem to get the permittivity of one of the layers. Simplifications are made, especially on the value of the 2nd layer compared to 1st one. This limits the method and gives non-precise results -if not totally false- for the value of permittivity of the thin film; and so iterative calculation is needed.

To simplify this problem, and avoid having faulty results, the microstrip line was deposited twice. One line is printed on an MgO substrate and the other on MgO substrate with BST film.

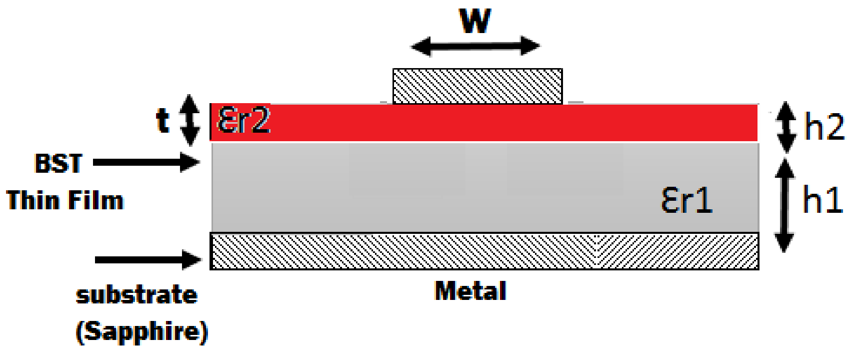


Figure 2. **BST film incorporated in a microstrip line.**

The measurement procedure is similar to that of the coplanar line. We use the transmission coefficient S_{21} and to deduce the effective permittivity of the system starting from the relation between S_{21} and the propagation constant mentioned before and valid for the case of planar transmission lines. Thus, for the 2 printed lines, we can obtain the effective permittivity with (loaded) and without (air) BST film. The measurement of the permittivity of the thin layer is made using the simple approximation described in [10]:

$$\varepsilon_{eff}(loaded) = \varepsilon_{eff}(air) + \varepsilon_{r2}.\frac{h_2}{w_{eff}} \tag{8}$$

The effective permittivity of the multi-layer system and the effective permittivity of the line with the substrate depend on permittivity of the thin layer and its thickness. Where $\varepsilon_{eff\,(loaded)}$ is the effective permittivity of the multi-layer system with the thin layer of BST, $\varepsilon_{eff\,(air)}$ is that without the thin layer, h_2 is the thickness of the thin layer and ε_{r2} is the permittivity of the BST film, and w_{eff} is the effective width expressed as follows:

$$w_{eff} = 120\pi \frac{h_1 + h_2}{Z_0 \varepsilon_{eff}(loaded)} \tag{9}$$

Where h_1 is the thickness of the MgO substrate and Z_0 is the characteristic impedance of the line.

Inversing the problem, we can easily extract the permittivity of BST with an error not exceeding 10%. Thus, giving an idea about the permittivity value and to be used for later comparison with other measurements.

3. PREPARATION AND CIRCUITS CHARACTERISTICS

The coplanar line is printed on a sapphire substrate of 500µm in thickness; the metallic layer thickness is 2µm. The line has the following geometrical parameters: strip width w=500µm, slot width s=200µm thus having a 50 Ω characteristic impedance line.
The microstrip line is printed on an MgO substrate of 500µm thickness and on another on which a BST film of 0.7µm thickness is deposited. The line width is 490µm of metallic thickness of 2µm and other side of the MgO substrate is covered by a metal plan.

4. EXPERIMENTAL RESULTS AND DISCUSSION

To extract the complex permittivity from the ferroelectric thin layer starting from the measurement of the transmission coefficient of the coplanar line, we carried out a program under "Matlab". The permittivity of the ferroelectric thin layer is calculated starting from the equations previously mentioned. Since electromagnetic energy is mainly confined between the central conductor and the ground planes and being given the strong thickness of the substrate compared to that of the layer, the influence of the back side of that last on the electromagnetic distribution of the fields inside the coplanar line can be neglected. In the electromagnetic analysis, the substrate of the thin layer can thus be supposed of infinite thickness, which makes it possible to simplify calculations. A "SOLT" calibration was made with a special planar kit provided by ANRITSU.

The reference planes are moved to the line edges, thus at the end of the calibration procedure, we have a line of propagation of 20mm in length. The main idea was to design a test cell of great sensitivity by privileging the interaction wave-film at the longest possible distance, knowing that the thickness of film is very small. It is then a question of locating film at a place of the coplanar line where electromagnetic energy is strongly concentrated. This is why, metallization (central conductor and the 2 reference plans) are directly deposited on the film.

As we already indicated, the film is deposited on sapphire. Sapphire is anisotropic; the sapphire permittivity given by the manufacturers is 9.4 in plane-a and 11 in the plane-C. In measurements, generally, a median value of 10 is taken which can induce some errors as far as the permittivity of the thin layer is related. In our work, because the circuit was printed on virgin sapphire too, we measured the permittivity of the sapphire, which is normally considered to be that in the plan-C according to the supplier (parallel plane). Measurement gave the following result (Fig. 3):

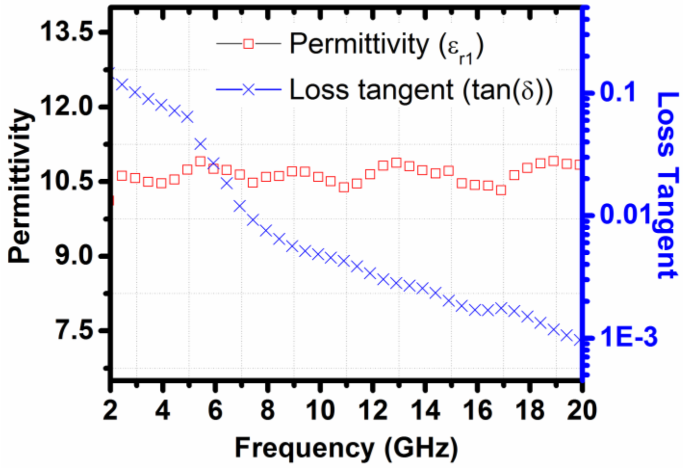
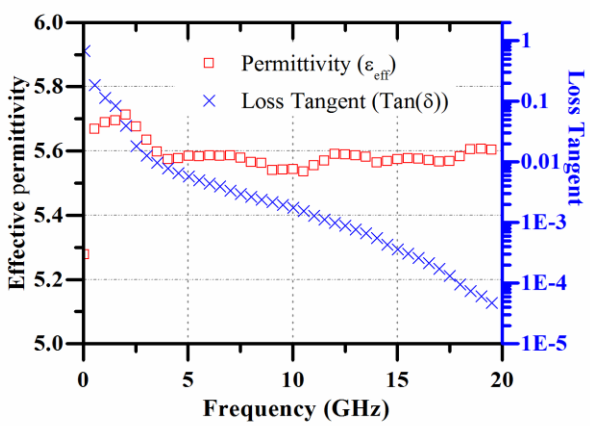


Figure 3. **Relative permittivity and loss tangent of sapphire Substrate.**

The value of the permittivity is found to be around "10.7" approximately equal to that given by the manufacturer.

We followed the same procedure and we measured the permittivity of the BST film. To illustrate the experimental results obtained starting from this procedure, Fig.4 (a) shows the effective permittivity measured for the line integrating the thin layer of BST of thickness 0.7µm.



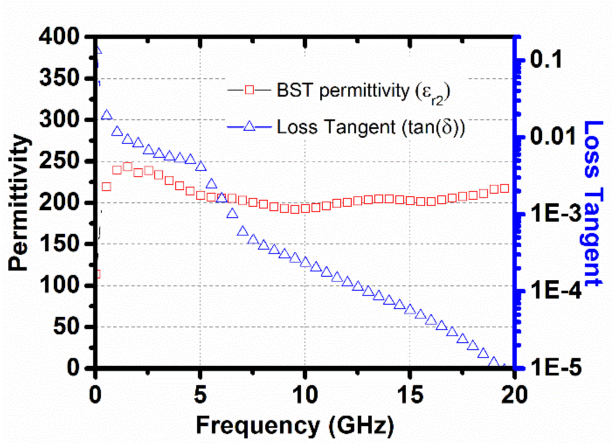


Figure 4. **(a) Effective relative permittivity of the system (b) Relative permittivity of the ferroelectric thin layer.**

The permittivity of the ferroelectric thin is shown Fig.4 (b), the spectrum of the real part is around 200 on the exploited band (0-20 GHz), and that of the loss tangent between 10^{-2} and 10^{-5}. One notes some dispersion in the measured permittivity of the thin layer (value of the real part ranging between 200 and 250). The loss tangent as well does not have any precision, with a value which varies between 0.01 and 10^{-5}. The inaccuracy and limitation of the loss analysis of the circuit stands behind the dispersion and inaccuracy of the obtained results specially the loss tangent result.

Following the same procedure as for coplanar, we measured the permittivity of the MgO substrate on which the microstrip line is printed and that of the BST film. The results for MgO and thin film are presented in the following figure (Fig. 5):

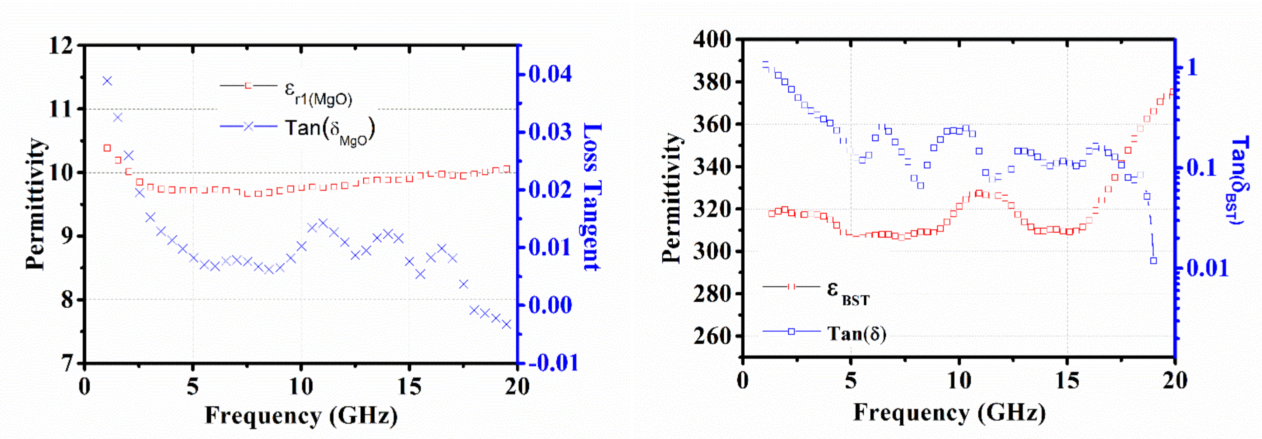


Figure 5. **(a) MgO dielectric constant and (b) BST film permittivity and loss tangent.**

The measurement of the transmission coefficient S_{21} was not totally clean; the printing of the line wasn't perfect and so a number of small resonances occurred in the S_{21} response which affected the results and were noticed along the frequency band. In addition, a calibration problem was observed at high frequencies, so, result can be considered up to 17 GHz which seems satisfactory. Resonances do not seem to have an important effect on the permittivity contrary to the losses tangent. Left to say, that no losses analysis was done, neither metallic nor dielectric losses; only the imaginary part of the permittivity of the substrate is included in our calculations, which explains the high value for the loss tangent.

At first sight, one can clearly notice for the permittivity of the thin layer, the difference between the values measured with microstrip method and those measured with the destructive coplanar line method.
The summary of the results obtained are presented in Table 1 and a permittivity comparison for both structures in Fig. 6:

Table 1 Methods used and values of BST obtained

Method	Measurement type	Frequency range	Substrate	Permittivity BST
Coplanar line	Destructive/ transmission	0-20GHz	Sapphire	200
Microstrip line	Destructive / transmission	0-20GHz	MgO	320

It is good to note here, that the BST-coplanar is deposited on sapphire substrate while BST-Microstrip is deposited on MgO. So the obtained result depend on the substrate used, and this can validates the hypotheses of the effect of the type of substrate on the value of the permittivity of the ferroelectric film, at least for our BST used.

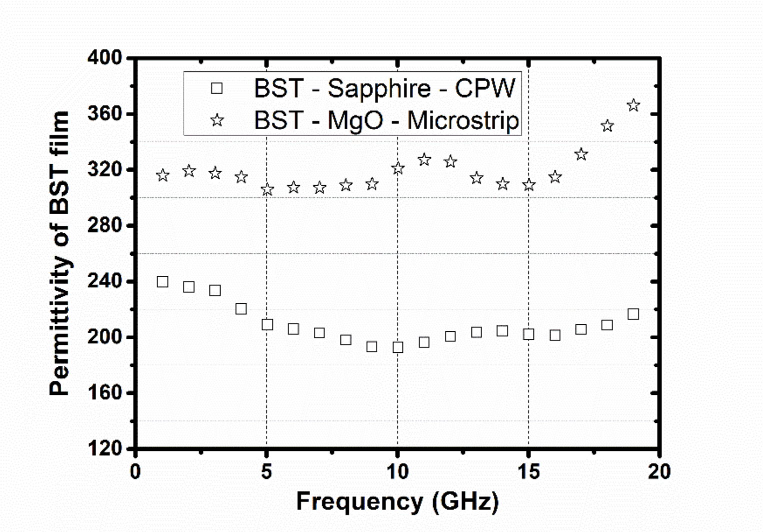


Figure 6. **Comparison between the 2 BST films permittivities measured using both methods.**

5. CONCLUSION AND COMPARISON

In this paper, two methods of characterizations were presented in order to compare the permittivity of ferroelectric thin films materials. The methods are both destructive thus no air gap problem present as in non-destructive methods. The frequency range covered for the measurement went up to 20 GHz. The results obtained are satisfactory from permittivity point of view in comparison to those values presented in the literature for such type of material, but less meaningful from that of loss tangent values with an average of 10^{-3} for coplanar line method and a higher value for that of other method which can be referred to the non-precision of the model for calculating the losses. The difference between the values of permittivity measured with microstrip method and those measured with the destructive coplanar line method proves the dependency of the substrate type on the characteristic of the deposited films.

6. ACKNOWLEDGMENT

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