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Thin BST Films Materials Measurement: Reflection Type Planar Circuits' Methods Comparison

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Abstract— this paper presents a comparison of different planar transmission line dielectric measurement methods. The measurement is made on B60S40T thin films samples deposited on MgO and sapphire with a thickness of 700nm. The work discusses the Reflection measurements methods.

The measurement methods use 2 types of transmission lines: «coplanar line» and «Microstrip line». Three different reflection methods: «patch antenna», «Coplanar resonator» and «Microstrip ring resonator» are introduced. The presented methods are destructive ones with measurement results obtained for the permittivity at resonant frequency up to 20 GHz. Subsequently, a review of these different methods is presented.
Index terms -permittivity, dielectric constant, thin films, patch, ring resonator, coplanar resonator, conformal mapping.

I. Introduction

A big share of the advance in technology and miniaturization return to the integration of new smart materials into devices. Among these materials comes, "Ferroelectrics". A class of dielectrics with large values of dielectric constant that can be tuned by an externally applied electric field. These materials are of great interest in the microwave range because of this. A changing dielectric constant offers a changing phase shift to an EM wave passing through it, which lures ferroelectrics attractive for such 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. One other 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 applications, a measure of their dielectric properties is required. A study of different planar destructive methods of characterization has been studied and tested here. Opening the way to their characterization under the application of a DC voltage to show the tenability in permittivity and thus the performance of the material in different applications.

Our work is directed towards the study of various devices either at low frequencies, or high frequencies, in reflection with open-circuits (the open circuit structure was retained because of its easier technological realization in comparison with short-circuit and also for later field applications) or in transmission. As already been indicted, the circuits used are reflection type ones or at resonant frequency measurements we used: "a coplanar resonator, ring resonator and an antenna patch". In order to improve our structures, a number of simulations were carried out using two commercial EM softwares: "ANSOFT HFSS" and "CST Microstripes".

II. Patch Antenna:

(A) Theory and Formulation:

One of the simplest devices for measurements is the microstrip patch antenna. With its theoretical formulas well defined, it is possible to relate the resonance frequency to its dimension (half wavelength) and thus, the simplicity of the data processing. In order to simplify the analysis, the patch is generally of form square, rectangular, circular, triangular, elliptic or another common form. The formulas employed during our measurements whether that's of the effective permittivity or the characteristic impedance are cited [1, 2]. An antenna of half wave length has its resonance frequency deduced from the following:

$$L \approx 0.49\lambda_d \qquad (1)$$

Where λ_d is the wave length in the dielectric and written as $\lambda_d = \lambda/(\varepsilon_{eff})$, L is the length of the patch and ε_{eff} is the effective permittivity of the structure.

(B) Preparation:

The patch is printed twice. One time on MgO substrate and the other on MgO having this film deposited on it.

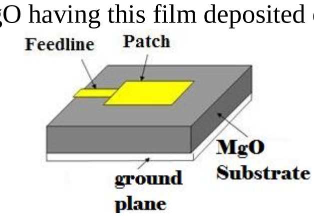

Figure. 1: Rectangular patch antenna.

The patch feed-line is engraved on the same substrate to provide a planar structure. The dimensions are the following: width W= 5.4mm, length L= 4.4mm. Length of the feed-line=3mm, width=500µm, and metal thickness of 2µm.

(B) Results:

The measurement of the permittivity of the ferroelectric thin layer with the rectangular patch is conducted through finding the effective permittivity then inverse problem to extract the material permittivity. Yet, this time the measurement of the effective permittivity is made at the resonance frequency of the patch, it is thus a mono-frequency measurement. The following figure show the reflection coefficient of the system in both cases: air (index v) and with the BST layer (index c).

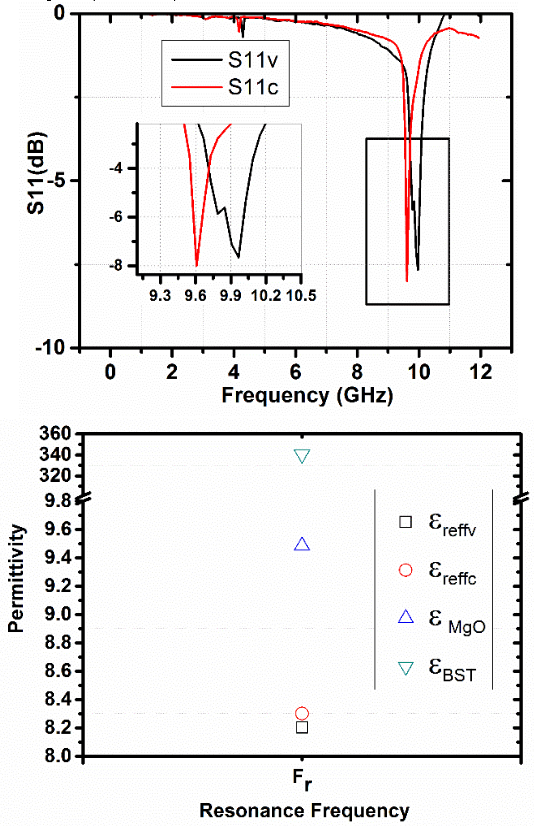

Figure. 2: (a) The reflection coefficient in air and with BST, (b) the results obtained for the different cases.

The rectangular antenna gives a resonance frequency fr =10.027 GHz in the case without BST and fr = 9.967 GHz with the BST layer. We measured the effective permittivity at the resonance frequency using:

$$\varepsilon_{eff\,(with material)} = \varepsilon_{eff\,(without material)} + \varepsilon_{material} \cdot \frac{h_{material}}{w_{eff}} \qquad (2)$$

and then we deduced the permittivity of the MgO substrate and that of the thin BST layer. As shown in the Figure, the effective permittivity is respectively 8.203 for MgO alone, and 8.302 when charged with BST.

Thus, for the 2 printed lines, we can obtain the effective permittivity with (charged) and without (air) BST film. The measurement of the permittivity of the thin layer is made using the simple approximation described in [3]:

$$\varepsilon_{eff\,(charged)} = \varepsilon_{eff\,(air)} + \varepsilon_f \,.h_f/w_{eff} \qquad (3)$$

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 εeff (charged) is the effective permittivity of the multi-layer system with the thin layer of BST, εeff (air) is that without the thin layer, hf is the thickness of the thin layer and εf is the permittivity of the BST film, and weff is the effective width expressed as follows:

$$w_{eff} = 120\pi\,(h_s+h_f)/(Z_0\,\varepsilon_{eff\,(charged)}) \qquad (4)$$

Where hs is the thickness of the MgO substrate and Z0 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 will be used to compare later on with other measurements.

The permittivity of MgO is of 9.4857 and the permittivity of thin film is deduced to be εf =340.54. The measured results approaches those obtained previously with the microstrip line.

III. MICROSTRIP RING RESONATOR:

(A) Theory and Formulation:

This method uses a microstrip ring resonator. Resonance is possible when the following condition is valid [4,5]:

$2\pi r_m.\ \beta = 2n\pi$ (5)

With n = 1, 2, 3… and "β" the phase constant along the microstrip line defined by: β = nπ / *l* where "*l*" is the resonance length related to the wave length $\lambda_d=\lambda/\sqrt{\varepsilon_{eff}}$, "$r_m$" is the average radius of the ring and ε_{eff} is the effective permittivity.

To evaluate the effective permittivity using a ring resonator, one can simply measure the resonance frequency of order s: "$f_{r,S}$" and extract "$\varepsilon_{eff,s}$" from the following formula:

$$\varepsilon_{eff,s} = [s.c/(2.\pi r_m f_{r,s})]^2 \qquad (6)$$

The measurement of the resonance frequency is usually made with a network analyzer, coupled with the ring resonator by two microstrip lines of 50Ω.

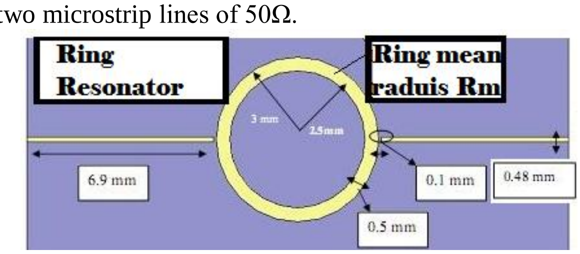

Figure.3: Ring resonator.

The ring resonator is printed twice, on the same substrates next to the microstrip patch presented previously. According to Figure, the average radius "r_m" is of 2.75mm, the feeders are 6.9mm each and the slot gap "s" between the ring and the feeder is 100μm.

(B) Measurement results:

The research of the value of the permittivity of the thin layer is rather difficult in the case of the ring resonator. No simple formula can make it possible to extract a precise value for thin film. For that, the study will be made here using a curve fitting with Ansoft HFSS. The effective permittivity can be deduced from equation presented above, starting from the resonance frequency. The responses of the transmission and reflection coefficients are presented in the following figure (Figure (a).):

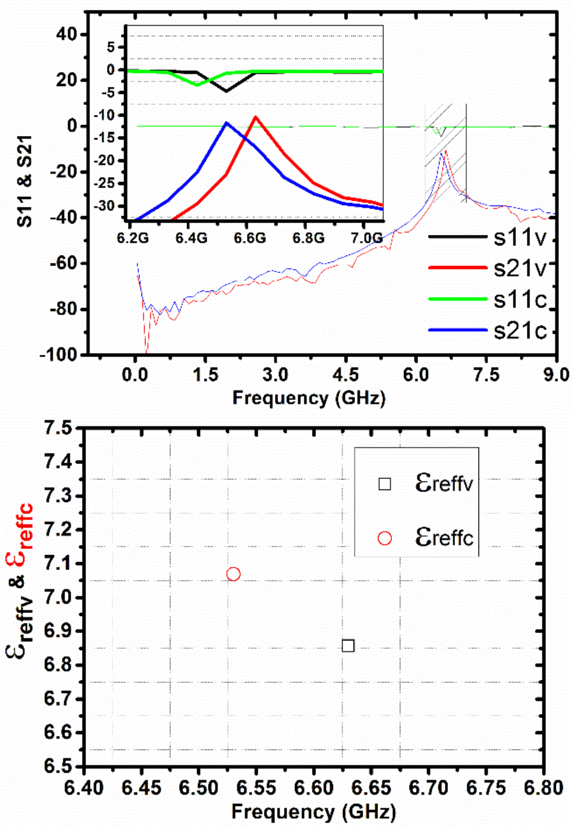

Figure. 4: (a) Ring *resonator:*S_{11} *(dB) and* S_{21} *(dB)*, (b) effective permittivity with 'c' & without 'v' BST.

The effective permittivity with 'c' & without 'v' BST is presented in Figure (b). We have, $\varepsilon_{effv}=6.8578$ at a frequency f_r =6.63GHz for a one layer system and ε_{effc} =7.0696 at a frequency f_r =6.53GHz for the 2-layers system.

(C) The HFSS simulation and results fitting

To extract the permittivity of the thin film we launched a simulation process on commercial simulation software based on FEM.

We'll simulate the same resonator printed with a 0.7µm film thickness for different permittivity values and try to fit the resultant resonance frequency for each case with that obtained from measurement (f_r =6.53GHz).

The simulation time was significant. Having an idea about the result, we took a value of 9.45for the permittivity of MgO substrate and a permittivity for film varying between 300 and 400 of step of 20.

The resonant frequency seems to be 6.43 GHz for the permittivity value of 320 and 6.8 GHz for the permittivity value of 300. This convinces us to some level that the value of the permittivity falls in this range.

(D) Conclusion and comparisons

The obtained results seem to confirm those measured above for patch. The results fall in the same permittivity band [300 - 340] for the permittivity of the thin film deposited on MgO substrate.

The following part, will be devoted to measurement with circuit of the coplanar type, which generally presents advantages compared to the microstrip for later use in dynamic measurement.

IV. COPLANAR RESONATOR:

(A) Theory and Formulation:

A coplanar resonator is used here to study the characteristics of the thin BST film. The resonator structure is shown in Figure. The resonator consists of a simple half-wavelength coplanar waveguide (CPW) resonator, which can be used to investigate the resonant frequency shift.

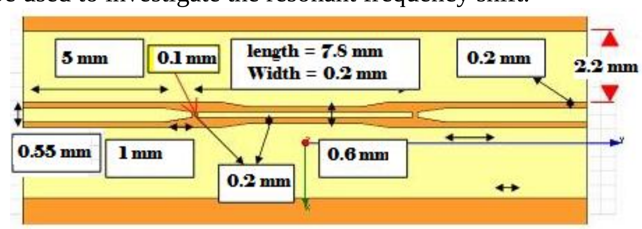

Figure. 5: The coplanar resonator structure.

The resonance frequency of such structure is represented in the following equation [6, 7]:

$$f_0 = c/ [l. (\varepsilon_{eff} .\mu_{eff})]^{½} \quad (7)$$

Where 'c' is speed of light in vacuum, l=7.8mm is the length of resonator, ε_{eff} is the effective permittivity, and $\mu_{eff}$is the effective permeability (≈ 1).

The overall length of the device is 20mm; the metallic thickness is always 2µm. The length of the resonator line is 7.8mm or 1/2 wavelength and its width is 0.2mm. The entries on each side are of 50Ω. The gap between the resonator line and the feeder is 0.1mm.

The method followed for measurement of the complex permittivity of BST ferroelectric material is similar to that followed for patch. Where, the effective permittivity is deducted from the equation presented above starting from the measured resonance frequency. Then, the conformal mapping method cited in [8, 9] is used to represent our multi-layered system. The simplified formula for a 2-layered structure is given by:

$$\varepsilon_{eff} = 1 + q_1(\varepsilon_{r1} - 1) + q_2(\varepsilon_{r2} - \varepsilon_{r1}) \quad (8)$$

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. 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) Preparation and circuit characteristic

The circuit is printed twice: on BST film of 0.7µm thickness deposited on the sapphire substrate and second time on sapphire. The sapphire substrate is 500µm in thickness; the metallic layer thickness is 2µm.

(C) 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 ribbon 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.

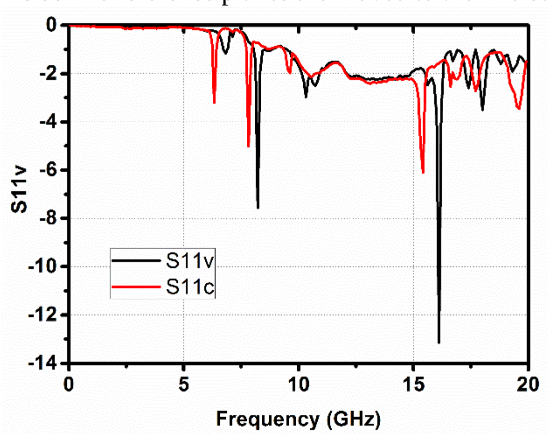

Figure. 6: Coplanar resonator: S_{11} (dB) with (c) and without (v) BST.

As we already indicated, the film is deposited on sapphire. Sapphire is anisotropic; the sapphire permittivity given by the manufacturers is 9.4 in plan-a and 11 in the plan-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. 6):

The measurement gave the following results: f_r =8.226GHz (principal resonance) in the case without BST and f_r =7.827GHz with the BST layer. The effective permittivity gives $\varepsilon_{reff,v}$= 5.46, and $\varepsilon_{\mathrm{reff,c}}$=6.03 where '*v*' and '*c*' are for system without and with BST film.

By applying the same inverse problem as in the case of the destructive coplanar line, one obtains: ε_r=10.52 for the permittivity of sapphire. And the permittivity of the thin film is: ε_f =201.02. A measurement comparable with that obtained with the destructive coplanar line method.

The measurement done at the 2nd harmonic frequency that is, at 15.4 GHz and 16.1 GHz respectively gave: ε_r =11.02 for the permittivity of sapphire, and ε_f =185.66 for the permittivity of thin film. The results fall always in the same interval of permittivity with less than 8% error.

V. CONCLUSION

In this paper, different methods of characterizations are presented in order to compare the permittivity of ferroelectric thin films materials using various planar characterization methods. The results obtained are presented in the following table, we add to these results, other results obtained through 2 measurements cited in **[10]**, done previously using coplanar line and microstrip line. These lines were also deposited next to the other patch and ring resonator for microstrip and the coplanar was printed next to the coplanar resonator on the same substrate:

Table.1: Various methods used and various values of BST obtained.

Method	**Measurement type**	**Frequency range**	**Substrate**	**Permittivity BST**
Coplanar type measurement				
Coplanar line	Destructive/ transmission	0-20GHz	Sapphire	200
Coplanar resonator	Destructive / reflection	mono-frequency	Sapphire	201.02
Microstrip type measurement				
Microstrip line	Destructive / transmission	0-20GHz	MgO	320
patch Antenna	Destructive / reflection	mono-frequency	MgO	340
Ring Resonator	Destructive / reflection	mono-frequency	MgO	320

The results obtained make it possible to have an idea on the permittivity of the materials in hand.

If the circuits carried out in this study made it possible to validate a certain number of objectives, they also highlighted certain gaps in our way of taking measurements, in particular for the measurement of the loss tangent which is not possible with these methods. But, in spite of that, they allowed comparisons on the permittivity of BST.

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