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Dielectric Microwave Characterization of the SU-8 Thick Resin Used in an Above-IC Process.

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Abstract— A broadband technique for determining electrical properties of dielectric materials is presented, based on microstrip lines. Relative permittivity and Loss tangent are computed from S -parameter measurements and analytical equations. The analytical computation is either direct by using equations derived from Bahl formulas, or iterative by using Jensen-Hammerstad formulas coupled with the efficient secant algorithm. Thin film microstrip transmission lines have been fabricated for the extraction of dielectric electrical properties of SU-8 resin. A relative dielectric constant of 2.85 and a loss tangent of 0.04 were determined. These values are used in an EM simulator for the design of an SU-8 based High-Q inductor implemented on a low resistivity silicon substrate. The good agreement between measurements and simulations validates the characterization procedure and confirms the relevance of SU8 for applications up to 15 GHz.

I. INTRODUCTION

Current developments of mobile telecommunications are accompanied by an increasing demand for powerful, low cost and reliable new technologies. In addition, the increasing complexity of circuits implies the use of electric and electromagnetic (EM) simulators to carry out effective designs. However, simulations require a good knowledge of the electrical properties of involved materials, in particular of dielectric ones.

In this paper, two simple yet accurate dielectric constant and loss tangent extraction methods are presented. These methods are applied to the measured S -parameters of microstrip lines. One method is based upon direct analytical calculations while the other relies on an iterative algorithm. These methods are extremely fast compared to previous ones [1] since they do not require direct and inverse problem solving as well as a comparison between calculated and measured S -parameters.

After validation on an Alumina substrate, these methods were used to investigate the electrical properties of the epoxy based photoresist SU-8. The SU-8 appears as an attractive material for above IC process, because of its moderate mechanical strain and because it allows important thickness. This material has been previously characterized by using different techniques and methods. However, they either required a complex fabrication process [2] or showed inaccurate results [3]. In addition, several different types of SU-8 are available whose electrical properties are sensitive to processing conditions. For all these reasons, effective dielectric parameters extraction methods are needed, and hereby presented.

In order to characterize the SU-8 and to check the validity domain of the extraction methods, several microstrip lines with various widths w , resin Heights h , Lengths l and metal thicknesses t have been implemented. Then, potential applications of the SU-8 are investigated through the design, the realization and the characterization of a high-Q inductor integrated on a SU-8 layer deposited above a low resistive silicon substrate.

II. PROCESSING METHODS

The extraction of the dielectric electrical characteristics requires the calculation of the complex effective permittivity ϵ_{eff} from S -parameters (extracted from on-wafer measurements on a microstrip line). Next, the relative permittivity ϵ_r (real part of the complex permittivity $\epsilon_r = \epsilon_r' + j\epsilon_r''$) is computed using ϵ_{eff} and the microstrip physical dimensions. Finally, the loss tangent is determined. We present all these steps hereafter.

A. Extraction of the effective permittivity

The Reflection-Transmission method [4] is used to extract ϵ_{eff} from measurements. It requires the characteristic impedance value of the microstrip line into air (which is approximately constant). This value can be obtained from Jensen-Hammerstad's formulas [4].

Thus, the complex effective permittivity ϵ_{eff} is calculated using equations (1) to (4) below:

$$P = |P| e^{-j\varphi} \quad (1)$$

$$\gamma = \frac{1}{l} \cdot \ln\left(\frac{1}{|P|}\right) + j \frac{-\varphi}{l} \quad (2)$$

$$\gamma_0 = j \frac{\omega}{c} \quad (3)$$

$$\epsilon_{eff} = \frac{\gamma}{\gamma_0} \cdot \frac{1-\Gamma}{1+\Gamma} \cdot \frac{Z_c}{Z_0} = \epsilon_{eff}' - j\epsilon_{eff}'' \quad (4)$$

Where:

P propagation factor, Γ reflection coefficient [5]

γ_0, γ free space and material propagation constant

l physical length of the microstrip line

Z_c characteristic impedance of the microstrip line with air as dielectric; $Z_0 = 50 \Omega$ the reference impedance

Once ϵ_{eff} extracted, users can inject its value in one of the two following methods to compute the relative permittivity of the dielectric material.

B. Computation Method 1

This analytical method is a direct computation of the relative permittivity ϵ_r . It uses equations derived from Bahl's formulas (based on Schneider model) [6]. Using a simple formulation this method is very fast to compute. The extraction of ϵ_r proceeds as follow:

$$\epsilon_r' = \frac{\epsilon_{eff}' - 0.5 + x/2 - y}{0.5 + x/2 - y} \quad (5)$$

$$\text{with } x = \begin{cases} \left(1 + 12 \frac{h}{w}\right)^{-0.5}, & \frac{w}{h} < 1 \\ \left(1 + 12 \frac{h}{w}\right)^{-0.5} + 0.04 \left(1 - \frac{w}{h}\right)^2, & \frac{w}{h} \geq 1 \end{cases} \quad (6)$$

$$\text{and } y = \frac{t}{7.8h\sqrt{w/h}} \quad (7)$$

Equation (7) is a correction function on ϵ_r to take into account the metal thickness. Bahl originally introduced a coefficient of 4.6 into the denominator leading to a precision within 2% for $t/h \leq 0.2$. However, during our experiments (see § II.E.), we found that ϵ_r was systematically overestimated for important values of the t/h ratio (structures with t/h ranging from 0.08 up to 1 have been processed). With a coefficient of 7.8 instead of 4.6, results match far better all over the selected t/h as demonstrated in § II.E.

C. Computation Method 2

This second method is derived from Jensen-Hammerstad's model [4]. Because of the formulas complexity (involving hyperbolic functions and natural logarithm), an iterative computation method is required. This process is realized using the secant algorithm (Fig. 1). The correct ϵ_r value is reached after convergence. The algorithm injects arbitrary ϵ_r values into Jensen-Hammerstad formulas and compare the resulting ϵ_{eff}' effective permittivity with the one extracted from measurements.

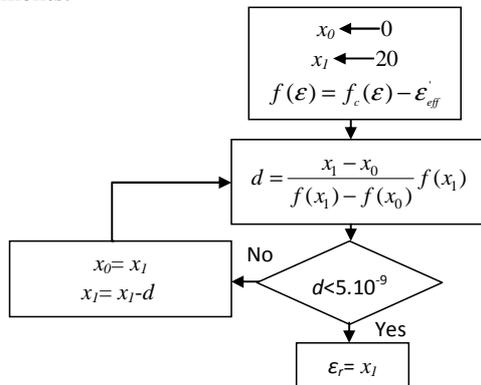


Fig. 1 Flowchart of the Secant algorithm

Where:

$f_c(\epsilon)$ function that calculates ϵ_{eff}' using Jensen-Hammerstad formulas; ϵ the predicted relative permittivity.

d error function; in conjunction with the value 5.10^{-9} it defines the conversion criteria.

x_0 and x_1 are variables needed to predict ϵ_r . They specify a range for its lowest and highest value.

D. Computation of loss tangent

In references [2] and [3], the loss tangent $\tan\delta$ is derived from the RLGC model of a transmission line. This gives accurate results only if the propagation in the structure is TEM (i.e. the structure involves a single dielectric). This condition is fulfilled in [2] but not in [3], which then reports the effective $\tan\delta$ values instead of the relative values.

This limitation can be overcome by using the equation [8]:

$$\tan\delta = \frac{\epsilon_{eff}''}{\epsilon_{eff}'} \cdot \frac{1 - 1/\epsilon_r}{1 - 1/\epsilon_{eff}'} \quad (8)$$

This equation is specific to microstrip transmission lines, which matches our work.

E. Accuracy and validity range

Since the two previously described methods for extraction of the relative permittivity and loss tangent are based on analytical developments, their error rate and range of validity have been estimated using several microstrip lines of various widths w , resin heights h , lengths l and metal thicknesses t (Fig. 2). Ansoft's 3D Full-wave EM simulator (HFSS) was used to simulate our structures. The aim of this analysis is to extract values of relative permittivity ϵ_r and loss tangent $\tan\delta$ that are compared to arbitrary ones initially set inside EM simulation.

Results of this analysis are presented on Fig. 2. One can notice that the fully analytical Bahl based method (method 1) presents an average error rate less than 1% until $t/h < 1.2$ and increases up to 35% for higher t/h ratios, which is related to the limitations of Bahl's formulas. On the other hand, the Jensen-Hammerstad based extraction (method 2) presents an average error rate of less than 2% on wide ranges of form factors (t/h and w/h).

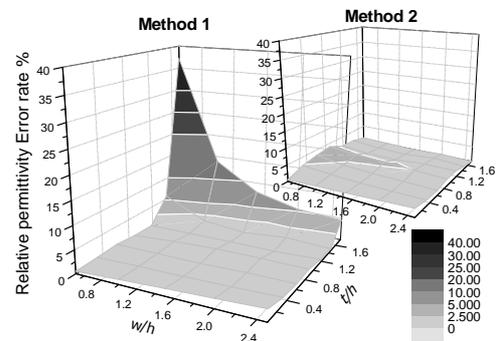


Fig. 2 Error rate evaluation for method 1 and 2 using EM simulation data.

As a conclusion, method 1, which is easily implementable into CAD tools, will be preferred until $t/h < 1.2$, while method 2 becomes useful beyond this limit.

III. MEASUREMENTS AND RESULTS

For a full validation of the extraction methods; a well-known dielectric material has been experimentally characterized. Measurements have been performed on a 0.2 cm long alumina based microstrip line issued from a Wiltron calibration kit (36804-15M). A TRL calibration procedure valid from 2 to 18GHz was previously applied. An ϵ_r of 9.96 and 10.1 and a 0.00025 $\tan \delta$ has been extracted at 10 GHz using methods 1 and 2 respectively (Fig. 3). These values fit very well to the ones announced by the manufacturer and the literature for a single frequency point ($\epsilon_r = 9.96$ at 10 GHz and $\tan \delta = 0.0002$). The accuracy of these two methods is hence demonstrated.

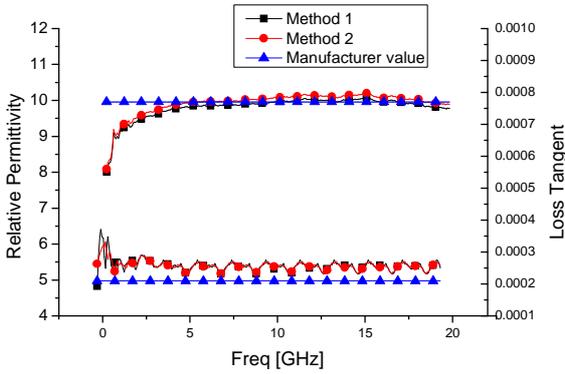


Fig. 3 Computed values of ϵ_r and $\tan \delta$ obtained from S-parameter measurements of an alumina transmission line.

A. Characteristics of the SU-8

A set of SU-8 based microstrip lines has been designed and fabricated to characterize the SU-8 resin and to provide additional verification of the methods accuracy.

A combination of 4 values of microstrip widths ($w[\mu\text{m}]$): 30, 60, 90 and 120) and of 3 lengths ($l[\mu\text{m}]$): 1000, 2000 and 3000) has been implemented (Fig. 4). Moreover, this combination has been repeated on 100 mm low-resistivity silicon wafers for several SU-8 heights ($h[\mu\text{m}]$) of 30 and 60) and metal thicknesses ($t[\mu\text{m}]$) of 5 and 30). The fabrication process consists in 3 metallization layers (Ground, vias and signal) and one SU-8 layer.

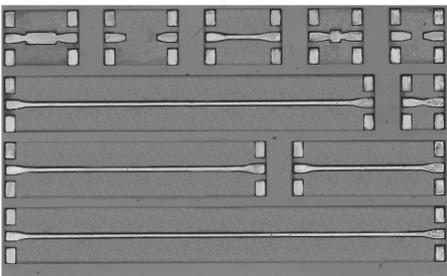


Fig. 4 Micrograph of SU-8 based microstrip set (lines and standards).

Metallization are processed by firstly evaporating a Ti/Cu seed layer followed by an electro-deposition of a thick copper layer. The dielectric layer is made by spin-on of SU-8 and subsequently a photolithography step for via opening. Contact pads were designed in order to fit commercial coplanar probes with a 150 μm pitch. Vias have been integrated for connecting the coplanar ground pads with the microstrip ground plane.

A vector network analyzer (Anritsu 37397C) and a probe station were used for microwave S-parameter measurements up to 40GHz. A SOLT calibration was performed to the locate reference planes at the probe tips and thru/open/short standards have been implemented and were used to de-embed the coplanar probing pads. S-parameter measurements were carried out on all microstrip structures but only results for 1000 μm lines are reported here.

The extraction procedures lead to an ϵ_r of 2.85 and a $\tan \delta$ of 0.04 at 25 GHz for the SU-8 resin, comparable to the values found in [2][3] (Fig. 5 and Fig. 6). Moreover, we can notice that these values are quite constant on the overall frequency range regardless of the microstrip line physical dimensions. The small variations can be related to systematic errors such as probe contact, positioning uncertainties or other imperfections in the fabrication process.

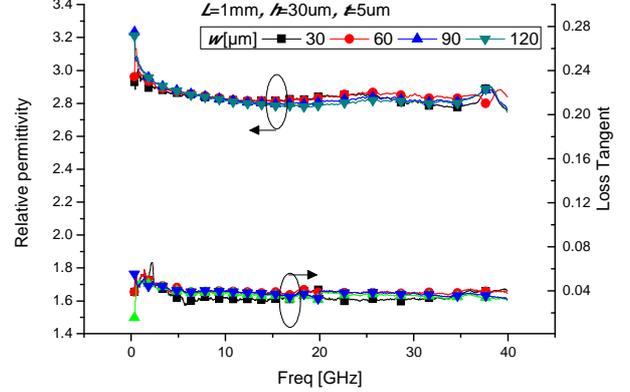


Fig. 5 Experimental ϵ_r and $\tan \delta$ for a set of microstrip lines with different widths w , $l = 1000 \mu\text{m}$, $h = 30.5 \mu\text{m}$, $t = 5.1 \mu\text{m}$; Extraction method 1.

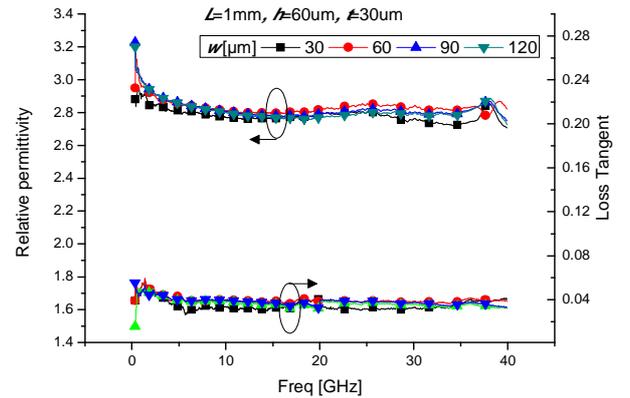


Fig. 6 Experimental ϵ_r and $\tan \delta$ for a set of microstrip lines with different widths w , $l = 1000 \mu\text{m}$, $h = 60.8 \mu\text{m}$, $t = 29.8 \mu\text{m}$; Extraction method 2.

B. High-Q inductor measurement

Previous measurements demonstrate the relevance of the SU-8 resin for the development of a low loss RF above-IC process. Such a technology can be a low cost solution for the integration of high- Q passive devices since it requires few additional masks. Its interest is demonstrated through the implementation of a high- Q inductor.

This structure has been optimized using EM simulations and extracted dielectric data of the SU-8. It is designed to be used in a circuit that requires high current distribution. A 30 μm thick copper metallization is grown by electro-deposition on top of a 60 μm thick SU-8 layer. Coplanar access pads with taper are implemented in the first port to enable on wafer characterization. The other port is shorted to ground using vias (Fig. 7). Short and open standards are realized to de-embed the access pads.

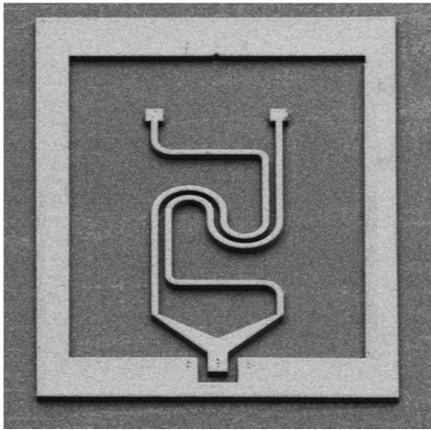


Fig. 7 SEM photography of an SU-8 based inductor

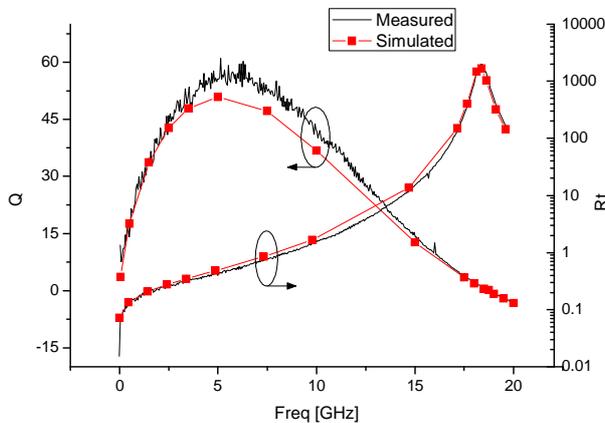


Fig. 8 Measured and simulated Q -factor and total resistance

Measurements performed on this inductor exhibit a Q value of 55 at 5 GHz for an inductance value of 0.7 nH (Fig. 8). Considering the inductor model defined in [9], total resistance R_t depicts the overall losses in the coil. Since the resonance frequency on R_t is related to the ϵ_r value and R_t level variation at high frequency is mainly derived from dielectric losses ($\tan \delta$), the excellent agreement between measurements and

simulations validates the relevance of the extracted dielectric parameters of the SU-8.

IV. CONCLUSION

In this paper, two dielectric properties extraction methods based on analytical developments of Bahl and Jensen-Hammerstad formulas are introduced. Their good accuracy over a wide range of microstrip lines is demonstrated and these methods are then successfully applied to characterize the SU-8. The extracted ϵ_r of 2.85 at 25 GHz with a loss tangent $\tan \delta$ of 0.04 confers to this resin some interest for above IC applications at RF frequencies. Finally, a high Q inductor is demonstrated using an above-IC process based on 60 μm thick SU-8 layer deposited on top of a low resistivity silicon substrate. Measurements show a Q value up to 55 at 5 GHz. This value and the good agreement with simulations confirm the design and the accuracy of the dielectric parameters extraction.

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