Modeling of Electromagnetic Behavior of Composite Thin Layers using Genetic Algorithm

Abdelmalek Reddaf1,2, Karim Ferroudji1, Mounir Boudjerd1, Khaled Hamdi Chérif1, Isslam Bouchachi1
1Research Center in Industrial Technologies CRTI. P.O. Box 64, Cheraga 16014 Algiers, Algeria
2Semiconductors and functional materials, Laboratory, University Amar Telidji Laghouat Algeria

Abstract— In this paper, we present a new model using the high frequency electromagnetic simulator for several binary mixtures where the load is in the lossless thin film form with a permittivity of (\(\varepsilon = 100, 200, 300, 400\)) and for various thickness values in a range of 10 \(\mu\)m to 250 \(\mu\)m with respect to the host matrix. The model operates in a variety of frequencies from 8.2 GHz to 12.4 GHz. The effective permittivity of composites is evaluated using Nicholson Ross Weir (NRW) algorithm in a rectangular waveguide. The implementation of NRW algorithm is conducted on various samples simulated by HFSS, in order to estimate the dielectric composite behavior. Furthermore, we employ a genetic algorithm methodology (GA) for the filling factor optimization of the proposed model by Mosallaei. The obtained results show a good agreement with the theoretical models, which ensure the validity of our proposed model for characterizing the electromagnetic behaviour of dielectric thin films.

Keywords— Thin films, electromagnetic behaviour, dielectric mixtures, Genetic optimization, microwave.

I. INTRODUCTION

MIM (Metal Insulating Metal) capacitors are commonly used for dielectric characterization of thin films [1]. However, at high frequencies or in the case of high permittivity, propagation phenomena appear and reduce the apparent permittivity. YILDIZ et al. [2] use the Conformal mapping method to calculate the effective permittivity of a composite in two phases, including a thin layer. This method suffers from a major drawback in the calculation of the permittivity which is not precise when the thickness of the thin layer is less than 10 \(\mu\)m.

The measurement technique in rectangular waveguide [3] has the advantage of being broadband, particularly in the X-and [8.2 - 12.4] GHz. On the other hand, the sample material to be characterized is placed in the interior of the structure of propagation (refer to Fig. 1).

We used HFSS software in the electromagnetic study of waveguide and broadband technique characterization of materials. This software is based on solving Maxwell’s equations, using the finite element method FEM, in the frequency domain. The simulator calculates the S parameters which are used to define the effective permittivity of samples using Nicholson Ross Weir (NRW) algorithm [4].

Figure. 1. The rectangular waveguide with the sample to be characterized (MUT).

Figure. 2. Sample load with a thin layer (thin film).

II. METHOD

A. The method of NRW

The electrical properties are obtained from S parameters. We describe the theoretical aspects of NRW method to obtain the effective permittivity for both the substrate and the thin layers (using different types of materials). The effective dielectric constant can be obtained from [3]:

\[
\varepsilon_{eff} = \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d_1 + d_2}
\]
B. Wiener’s model

Wiener [6] proposed a descriptive model of the effective permittivity of a composite for n components given by:

\[ \varepsilon_{\text{eff}}^{-1} = \sum_{i=1}^{n} f_i \varepsilon_i^{-1} \]  

(8)

\( \varepsilon_i \) is the relative permittivity of each layer; 
\( \varepsilon_{\text{eff}} \) is the equivalent permittivity of the multilayer;

C. Mosallaei’s model

The permittivity of the multi-layer substrate is given by H. Mosallaei [4], for a two layers we obtain:

\[ \varepsilon_{\text{eff}}^{-1} = f_1 \varepsilon_1^{-1} + f_2 \varepsilon_2^{-1} \]  

(9)

IV. RESULTS AND DISCUSSION

Table I illustrates the filling factors optimized for Wiener model using GA method.
TABLE I. FILLING FACTORS OPTIMIZED

<table>
<thead>
<tr>
<th>h1 (µm)</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>0.980</td>
<td>0.950</td>
<td>0.892</td>
<td>0.844</td>
<td>0.7909</td>
<td>0.745</td>
</tr>
<tr>
<td>f2</td>
<td>0.019</td>
<td>0.051</td>
<td>0.104</td>
<td>0.147</td>
<td>0.1969</td>
<td>0.2361</td>
</tr>
</tbody>
</table>

Filling factors are influenced only by the thickness of the composite material.

Fig. 4 shows the evolution of the equivalent permittivity of a multilayer composite in accordance with the thickness of the thin layer and for different values of the relative permittivity. We note that the change in the equivalent permittivity is a little large relative to the variance in thickness. This change becomes almost zero when the thickness is less than 10 µm.

In order to validate the obtained results, we compared the equivalent permittivity acquired using our proposed model with those obtained by GA model and Mosallaie model. The comparison is illustrated in Fig. 5, in which the results are quite similar.

Filling factors of GA model and Mosallaei models are very close, especially for $f_2$ in Fig. 6, this approach shows that the filling factors are influenced only by the thickness of the composite material.

V. MODELS VALIDATION

In the latter case, the performance of the filling factors of Mosallaie model compared to the filling factors of Wiener model is evaluated using various statistical indices [8] such as: Mean-squared error (MSE), Mean Absolute Bias Error (MABE), Root Mean Square Error (RMSE), and Relative Square Error (RRMSE):

The MSE gives the mean squared error. Its expression is given by:

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^{n} |H_m - H_{GA}|^2 \quad (12)$$

The mean absolute value of bias error is referred by MABE. Its expression is given by:

$$\text{MABE} = \frac{1}{n} \sum_{i=1}^{n} |H_m - H_{GA}| \quad (13)$$

Where $H_m$ is the filling factor of Mosallaie model value and $H_{GA}$ is the filling factor of GA model value.

The RMSE represents the difference between the predicted values (Mosallaie model value) and the measured values (the filling factor of GA model value). In fact, RMSE identifies the model's accuracy. It is calculated by:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (H_m - H_{GA})^2} \quad (14)$$

The RRMSE is calculated by dividing RMSE to the average of measured data as:
The performance of the model is defined by the RMSE range as follows: Excellent: RMSE <10%; Good: 10%<RMSE<20% ; Fair: 20%<RMSE<30%; Poor: RMSE>30%.

TABLE II. PERFORMANCE OF THE MODEL ACCORDING TO RMSE

<table>
<thead>
<tr>
<th>h1 (µm)</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>1.01%</td>
<td>2.00%</td>
<td>1.96%</td>
<td>2.84%</td>
<td>3.22%</td>
<td>2.89%</td>
</tr>
<tr>
<td>f2</td>
<td>0.91%</td>
<td>0.18%</td>
<td>0.55%</td>
<td>0.06%</td>
<td>0.05%</td>
<td>0.037%</td>
</tr>
</tbody>
</table>

Table. III and the curves in Fig. 7 illustrate that the error of the filling factors depends on the thickness of the thin layer which |f_{2m}-f_{2GA}| tends to zero if h2 decreases and |f_{1m}-f_{1GA}| tends to zero if h2 increases.

TABLE III. THE VARIOUS ERRORS BETWEEN THE FILLING FACTORS

<table>
<thead>
<tr>
<th>Error</th>
<th>MSE</th>
<th>MAE</th>
<th>RMSE</th>
<th>RRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>5.942e-004</td>
<td>0.0232</td>
<td>0.0244</td>
<td>2.86%</td>
</tr>
<tr>
<td>f2</td>
<td>1.975e-005</td>
<td>0.0029</td>
<td>0.0044</td>
<td>3.49%</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

In this paper a new model using the high frequency electromagnetic simulator for several binary mixtures is proposed. The Nicolson-Ross-Weir method is used as a numerical tool to estimate the value of relative complex permittivity of (MUT) over the X band. We estimate the dielectric composite behavior using simulation and GA approach. It should be noted that in this case the error of the filling factors depends on the thickness of the thin layer.

The obtained results are in a good agreement with the theoretical models, which ensure the validity of the algorithm for characterizing thin film dielectric media. The proposed model operates in a variety of frequencies from 8.2 GHz to 12.4 GHz.

VII. REFERENCES


