Extraction of (R,L,C,G) interconnect parameters in 2D transmission lines using fast and efficient numerical tools

F. Charlet*, C.Bermond** , S.Putot*, G. Le Carval*, B.Flechet**

*LETI (CEA-Technologies Avancées), 17 rue des Martyrs, 38054 Grenoble Cedex 09, FRANCE
**LAHC, Universite de Savoie, Campus scientifique, 73376 Le Bourget du Lac, FRANCE
phone :33 (0)476884894 fax :33(0)476889457 email : fcharlet@cea.fr

Abstract- **We present a new simulation method for a fast and efficient extraction of frequency dependant R,L,C,G parameters in 2D transmission lines structures embedded in a multilayered dielectric environment. Our method is based on two variational finite element formulations and use very efficient numeric tools (fictitious domain approach[1][2], fast solver, domain decomposition). It only needs an unstructured mesh of the conductors boundaries and is very efficient in memory and CPU time.**

The results are validated on test structures with an original method of measurements and characterization.
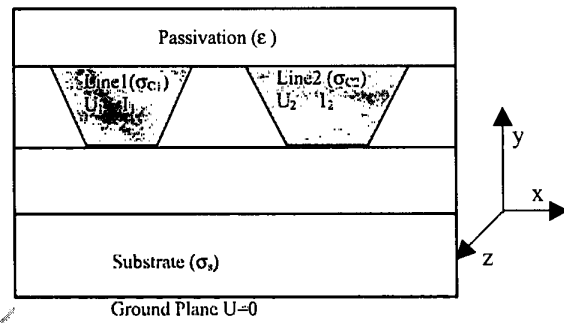
Fig 1 : Scheme of the structures.
(ε = permittivity; σ_{C1}, σ_{C2}, σ_s = lines ans substrate conductivities)

I. INTRODUCTION

In the transmission lines model, the electromagnetic field is transverse (TEM) and the problem may be restricted in a (x,y) cross-section of the structures (Fig.1). Electric potential is constant inside a conductor line section and we may construct a per-unit-length equivalent circuit dependent on the z direction. Working in the frequency domain $(U(z,t)=Real[\hat{U}(z)e^{j\omega t}])$, we obtain two independent linear systems that link the electric potentials $[\hat{U}_1(z)]_{l=1,...,N}$ and the currents $[\hat{I}_1(z)]_{l=1,...,N}$ in the N lines.

$$\frac{d}{dz}\hat{I}(z) = -Y\,\hat{U}(z) \qquad (1)$$

$$\frac{d}{dz}\hat{U}(z) = -Z\,\hat{I}(z) \qquad (2)$$

The (R,L,C,G) per unit-length matrices are obtained from the admittance matrix (Y=G+jωC) and the impedance matrix (Z=R+jωL). Equations (1) and (2) are associated with two variational formulations derived from the Maxwell equations which are described below.

II. ADMITTANCE MATRIX

To extract Y, we solve a set of N problems $(P_k)_{k=1,...,N}$. Problem (P_k) consists in calculating the electric potential $\hat{U}^k(x,y)$, solution of the differential equation (3) with the given conditions that $\hat{U}^k(x,y)=1$ inside the line k and $\hat{U}^k(x,y)=0$ inside the other lines and on the ground plane

$$\vec{\nabla}.\left(\varepsilon - j\frac{\sigma}{\omega}\right)\vec{\nabla}\hat{U}^k = 0 \qquad (3)$$

From the electric potential, we obtain the charge Q_{kl} of each line l and remark that $Q_{kl} = Y_{kl}/j\omega$.

Equation (3) is solved using the fictitious domain method that has been presented in [1][2] to calculate static parasitic capacitances in 3D interconnects. This method leads to a system that couples the potential and the surface charge of the conductors lines. The fictitious domain method uses a surface mesh of the conductors boundaries and an implicit regular mesh of rectangles that embeds the structure. Using the fast solver and the domain decomposition presented below, this method is very low memory and CPU time consuming.

III. IMPEDANCE MATRIX

To extract Z, we solve a set of N problems $(Q_k)_{k=1,..,N}$. Problem (Q_k) consists in calculating the magnetic transverse potential $A^k(x,y)$ when we impose the transverse electric field inside each line l ($d\hat{U}/dz=1$ in line k, 0 in other lines). $A^k(x,y)$ is solution of the system

$$\begin{cases} \Delta A^k - j\omega\mu\sigma_s A^k = -\mu J^k \\ J^k = -\sigma_{Ck} - j\omega(\sum_{l=1,..,N_l} \sigma_{Cl} A^k) \end{cases} \quad (4)$$

From the current density $J^k(x,y)$, we calculate the current vector $\hat{I}^k$ and remark that $\hat{I}^k$ is a column of the inverse matrix Z^{-1}.

We use a finite element formulation to approximate (4). The original point is that we use a regular grid of rectangles to define the finite element form functions ϕ_i. Technically speaking, one of the difficulties is to calculate the elementary term of the finite element matrix:

$$\int_{e \cap C_l} \sigma_{Cl} \phi_i \phi_j \, ds$$

where $e \cap C_l$ is the intersection of a rectangle mesh e and the line C_l.

As in the previous part, we use a fast solver associated to a domain decomposition method to solve the linear system.

IV. FAST SOLVER AND DOMAIN DECOMPOSITION METHOD

The principle of our fast solver was presented in [3]. It permits a fast computation of a linear system "$A\ X = B$" when A is a 'block tridiagonal with block" matrix. It is based on a matrix Fourier analysis and uses the FFT algorithm. The fictitious domain formulation of equation (3) and the first equation of (4) may lead to that sort of system if the following conditions are verified:

-The global domain of calculation Ω must be a rectangle and its approximation mesh must be a regular grid with a constant step in X-direction.

-The substrate and the dielectric layers must have a plane shape.

To avoid size problems due to the "constant X-step" condition, we use a domain decomposition method. Its principle is to define a first mesh Ω^0_h that embeds the lines with a fine X-step h^0_x and to add two meshes Ω^1_h and Ω^2_h with large X-steps h^1_x , h^2_x (see fig.2). We use an iterative algorithm that ensures the continuity of the unknown and of its normal derivative at the meshes interfaces.
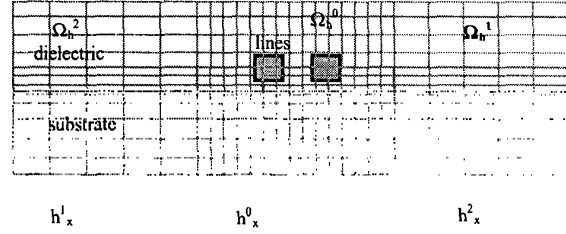

Fig. 2 . Domain decomposition . X-steps are constants/domain. Y-steps are variables. Surface lines mesh is independent from the mesh Ω_h^0

V. MEASUREMENT TECHNIQUES AND TEST STRUCTURES

The general principle of the test structures h as been published in [4], it permits to study the behavior of interconnects in environments representative of typical circuit configurations. In this paper, we present the results on an isolated long line(Metal 2= AlCu) with two specific configurations (Fig. 3.a, Fig. 3.b): either the lines "see" dense metallic lower levels (represented by a Metal, AlCu ground plane), or the Silicon substrate("Epitaxial" substrate, resistivity=0.01Ω.cm).

For measurements, a Vectorial Network Analyzer associated to a TRL (Through-Reflect-Line) calibration procedure performed in the range 40 MHz - 40 GHz has been used. This TRL method [5] [6] allows the measurement of the intrinsic S parameters from which the propagation coefficient γ of the line is extracted. To extract the elements (R,L,C,G), we use the following procedure: knowing that γ^2=(R+jωL)*(G+jωC) and calculating (C,G) with our simulation program, we are able to extract R and L from measurement of .γ This original measurements and characterization method is pr esented in [7].
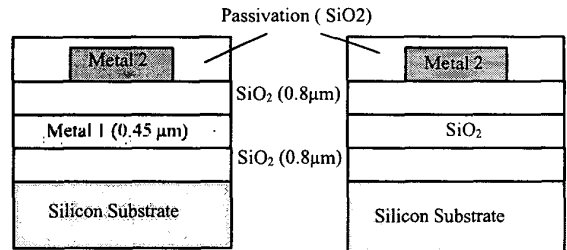

Fig 3.a   Fig 3.b

Scheme of test structures, the studied transmission lines are in Metal2 (4 µm wide, 0.7 µm thick and 0.5 to 10 mm long). Silicon Sub strate (Epitaxial) is 800 µm depth.

VI. RESULTS

In Fig. 4.a-4.b, we present comparative results on the measured and simulated values of R and L applied to the previous structures.

In the case of a line over Metal 1 (Fig. 4.a) the capacitance has been found constant (C=196 pF/m) and losses (G) is negligible over the whole range of frequencies. The comparison is fairly good (better than 10 %) over the whole range of frequencies.

The conclusions are different for Epitaxial substrate (Fig. 4.b) in which losses become important at High frequency, and have to be taken into account for a correct extraction of R and L from γ. The comparison is not so good but remains acceptable (max error 20 %). The difference might be explained by a less accurate knowledge of the current return path. Indeed, due to a lower conductivity in Epitaxial substrate than in metal, the lateral exten sion of the magnetic field is higher for the line over substrate (Fig. 5.b) and consequently, the effects of the distant neighborhood of the line are more important than for the line over Metal 1 (Fig. 5.a).
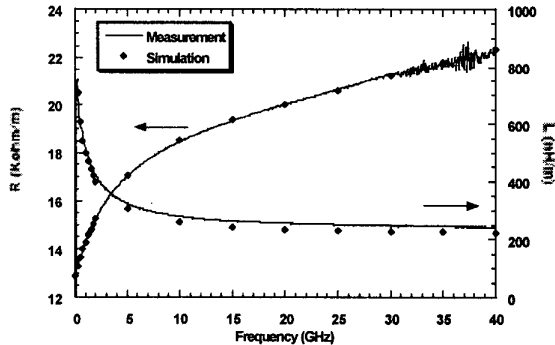
VII. CONCLUSION

We have presented a new program for (R,L,C,G) extraction in 2D transmission lines, based on very efficient numerical tools:

-We use a regular grid of the embedding domain that avoids the meshing of a complex domain and its storage.

-We use a FFT-based fast solver and a domain decomposition method, that makes the program low memory consuming and fast. For instance, we can obtain the 20 couple values of (R,L) of one of the previous results (fig 4.a or Fig. 4.b) in less than 10 minutes (Ultra 5 Sun station).

The simulation results are compared and validated with an original method of characterization on test structures produced at LETI and dedicated to the parasitic effects in interconnects.

Thanks to the efficiency of these tools in the 2D transmission lines problem, we expect to apply these methods on the 3D general problem. We also notice that our program is going to be introduced in a commercial software (Silvaco Data System).

REFERENCES

[1] S. Putot, F.Charlet, P.Witomski, "A fast and accurate computation of interconnect capacitance", IEDM99, pp 893 -897.
[2] S. Putot , F.Charlet, P.Witomski, "A new algorithm for interconnect capacitance extraction based on a fictitious domain method", SISPAD99.
[3] N. Swarztrauber,"The methods of cyclic reduction, Fourier analysis and the FACR algorithm for the discrete solution of Poisson's equation on a rectangle", SIAM Review, vol. 19, no 3, July 1977, pp. 490-501.
[4] C. Cregut, G. Lecarcal, J. Chilo, IITC'98.
[5] B. Flechet, R. Salik, J. W. Tao, G. Angenieux , "Microwave characterization of thin film materials for interconnections of advanced packaging" , IMAPS -ISHM, march 10-12, 1997, Braselton, Georgia.
[6] R. B. Marks, "A multiline method of network analyser calibration", IEEE Trans. on Microwaves Theory and Techniques, vol. 39, no 7, July 1991, pp 1205-1215.
[7] C.Bermond et al., workshop on Signal Propagation Interconnect 2000, Magdeburg, Germany (unpublished).

Fig. 4.a . Comparison of extracted and simulated resistances and inductances for a line over Metal 1 (case of Fig. 3.a).
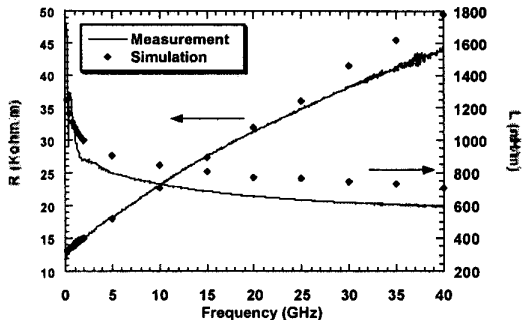

Fig. 4.b. Comparison of extracted and simulated resistances and inductances for a the line over the epitaxial substrate (case of Fig. 3.b)