Modeling and electrical characterization of parasitic effects for GaAs integrated circuits. Experimental validation and CAD formulas

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Abstract: ***This study investigates the computing of the inductance and capacitance coefficients of short links (gold wire connections, vias, interconnection crossing and coupled lines). The [L] and [C] matrix calculations are performed with the vector and scalar potential given in an integral form, taking into account the current density distribution on the conductors. Analytical formulas easy to use in CAD are derived from the numerical results using a least square method. The formulas have been shown to agree, with a precision in the order of 3%, with simulation results and with experimental results obtained on test boards in the frequency range 1-30 GHz.***

I. Introduction

In the past fifteen years, we have witnessed a spectacular development in the complexity and speed of operation of integrated circuits. One problem facing designers of integrated circuit packages is the accurate prediction of electrical performances before the fabrication process is sketched **[1]**. The continuous improvement of integrated circuit fabrication processes allows to increase the integration density. At high levels of integration, a large number of short interconnections is needed, which induces delays and interference. Besides the delay, mismatch and coupling effect due to long links (lengths comparable or greater than the wavelength), localized phenomena due to shorter links (lengths smaller than the wavelength) also disturb the signal propagation. For all these reasons, circuits simulators should take into account parasitic effects. Figure 1 illustrates a number of cases where interconnections give rise to parasitic effects: wire bonding, Tape Automatic Bonding (TAB), via hole, interconnection crossing, coupled line, ...

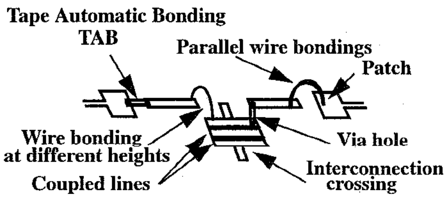


Figure 1: Some typical configurations of interconnections.

This paper presents a general approach for computing the inductance and capacitance coefficients of short links and for the evaluation of analytical formulas used in CAD. The second section presents the detail of the numerical approach. The capacitance and inductance coefficients involved in the equivalent model are calculated. To do this, the scalar and the vector potential are expressed in an integral form, taking into account the current density distribution and the charge density distribution on the conductors. In the third section, we present analytical formulas, easy to use in CAD systems, derived from the numerical results using a least square fit method, as well as a comparison of the predicted results with simulation results and with experimental results obtained on test units.

II- Formulation of the problem

Different geometries have been investigated (figure 2). Bonding wires and vias are generally described by an inductance whose value is determined from the potential vector integral **[2]**; interconnection crossings and coupled lines are generally described by capacitance whose value is determined from the potential scalar integral **[3]**.

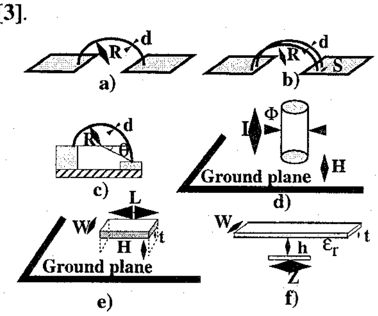


Figure 2: Different types of interconnections: a)- One wire bonding. b)- Two parallel wire bondings. c)- Wire bonding at different heigths. d)- Ribbon connection. e)- Via hole. f)- Interconnection crossing. g)- Coupled lines.

A. Calculation of inductance parameters

Bonding wires and vias are generaly discribed by an inductance whose value is determined from the potential vector integral. The [L] matrix calculation is performed with the potential vector given in its integral form **[2]:**

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \sum_{j=0}^{Nc} \int_{vol} \frac{J(\vec{r}_j)}{|\vec{r} - \vec{r}_j|} dS_j d\vec{l}_j \qquad (1)$$

The coefficients are difficult to evaluate analytically from the above integrals, since the current distribution is generally unknown and the shape of the conductors variable. We have thus used the Partial Element Equivalent Circuit method (P.E.E.C.) **[4]**

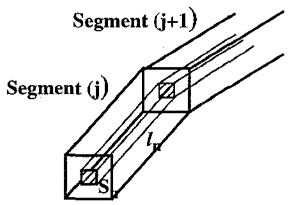


Figure 3: Subdivision of a conducting segment into elementary cylinders.

which consists in dividing the conductors into elementary cylinders where uniform current is assumed. Each elementary cylinder is represented by its partial resistance, its partial self and mutual inductances.

Each segment j (j = 1, 2, ... N) of a conductor is divided into N_j elementary cylinders of cross-section S_n and length l_n (figure 3). The average voltage across cylinder m is given by :

$$u_m = j\omega \sum_{j=1}^{N} \frac{1}{S_m} \int_{S_i}\int_{l_i} \vec{A}_{mj} d\vec{l}_m dS_m + \frac{i_m}{S_m} l_m \quad (2)$$

$\vec{A}_{mj}$ is the potential vector arising from elementary current Ij at point $\vec{r}_m$ on cylinder m.

Equation (2) is written for each cylinder j = 1, 2, ..., N_j, giving a system of N equations :

$$[u_m] = [S_{mn}][i_n] \quad (3)$$

$$S_{mn} = \frac{\mu_0}{4\pi} j\omega \frac{1}{S_n}\frac{1}{S_m} \int_{S_m}\int_{S_n}\int_{l_n}\int_{l_m} \frac{dS_n dS_n d\vec{l}_n d\vec{l}_m}{|\vec{r}_m - \vec{r}_n|} \quad (4)$$

In the partial inductances coefficients L_{mn}, self (m=n) and mutual ($m \neq n$) effects have been separated assuming elementary cylinders.

The self inductances can be found in several references **[2]**, **[4]**. The partial mutual inductance depends mainly on the geometrical positions and the length of the two segments and only slightly on the cross section shapes. Hence, in a first order approximation, we will calculate the filament inductances, assuming that the cross section of the two segments is much smaller than the segment lengths **[5]**.

B. Calculation of capacitances parameters

Interconnection crossings and coupled lines are generally described by a capacitance whose value is determined from the potential scalar integral.

The considered geometry is shown in figure 4. The electromagnetic problem is formulated by using free-

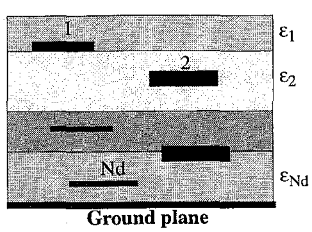


Figure 4: Multilevel interconnections in a multilayer.

space Green's functions. At any point $\vec{r}$, the scalar potential Φ is given by the well known relation:

$$\Phi(\vec{r}) = \sum_{j=1}^{N} \int_{S_j} \frac{\rho_T(\vec{r}_c)}{\varepsilon_0} [G(\vec{r}, \vec{r}_c) - G(\vec{r}, \vec{r}_c')] dS_c \quad (5)$$

where $\rho_T(\vec{r}_c)$ is the total charge density at r_c, and S_j is the boundary of the jth interface.

The total number of these interfaces is:

$$N = N_c + N_d - 1 \quad (6)$$

N_d is the number of the dielectric layers and N_c is the number of conductors,

dS_c is the differential element of length on S_j,

$\vec{r}'_c$ is the image of $\vec{r}_c$ about the main ground plane,

$G(\vec{r}, \vec{r}_c)$ is the Green's function in two-dimentional free space.

The problem is to find the total charge density distribution ρ_T taking into account the potential Φ. The real free charge density ρ_L, on the surface of each conductor, is determined by the boundary conditions. The capacitance coefficients C_{ij} between conductor i and j are found from the relation ship:

$$Q_i = \int_{S_i} \rho_L(r) dS_i = \sum_{i=1}^{N_c} C_{ij} \phi_j \quad (7)$$

where Q_i is the free charge of conductor i.

The Method of Moments **[6]** is used to solve integral equation (5). In order to determine the total charge density, all interfaces are divided into J elementary parts. A solution is obtained assuming the total charge density ρ_{Tn} on each partition n as constant; so the elementary total charge q_{Tn} on the partition of length Δl_n , is:

$$q_{Tn} = \rho_{Tn} \Delta l_n \quad (8)$$

The unknown q_{Tn} are determined using boundary conditions on each partition. Assuming the field and potential are constant and equal to their average value for each partition, the unknowns (q_{Tn}, n= 1, 2, ..., J) can be written in matrix form:

$$[K_{mn}][q_{Tn}] = [\Phi_m] \quad (9)$$

where $[K_{mn}]$ is a matrix determined from the potential continuity on the conductors held at voltage of ϕ_i and from the continuity of the normal component of the deplacement vector

The unknown q_{Tn} are obtained by:

$$[q_{Tn}] = [K_{mn}]^{-1}[\Phi_m] \quad (10)$$

From this result, the free charge density and the capacitance coefficients are then determined.

III- Analytical Formulas and comparisons with simulations and experimental results

Electromagnetic simulation techniques require large computer memories, long computing time and large data handling. For these reasons, they are difficult to use extensively in CAD systems. We have developed formulas for the following cases: one wire bonding, wire bonding at different heigths, two parallel wire bondings, ribbon connection (T. A. B.), via hole, coupled lines, and interconnection crossing. These formulas have been derived from numerical results using the least square method **[7]** and are of easy use. Geometrical and technological parameters are considered as input data.

Because of their empirical nature, these expressions are restricted to a specified domain of validity. We have limited the study to a particular domain of interest, but the method can obviously be applied to different domains of validity.

The simulations agree with a precision in the order of 3% with simulation results and with experimental results obtained on test boards in the frequency range 1-30 GHz.The paper will give, in table form, a summary of these results. We present below three specific cases: one wire bonding, two parallel wire bondings and ribbon connection.

III. 1- One wire bonding

In the case of one wire bonding, the analytical formulas have an accuracy of about 3% for the following set of parameters:

$$10 \le d(\mu m) \le 70$$
$$100 \le R(\mu m) \le 650$$
$$30 \le S(\mu m) \le 200$$

The detailed expression for this case is given below:

$$L(nH) = a(R^2) + \left(\sum_{i=0}^{2} b_i d^i\right)(R) + \left(\sum_{i=0} c_i d^i\right) \quad (11)$$

where a = 9.6786 10^{-7} and Table 1 lists the coefficients b_i and c_i (i = 1, 2)

	11	12	13	14
b_I	-4.63 10^{-9}	7.54 10^{-7}	-5.48 10^{-5}	0.0032
c_i	3.24 10^{-8}	-6.52 10^{-6}	8.829 10^{-4}	-0.0835

Table 1: Coefficients b_i and c_j for the case of one wire bonding.

III. 2- Two parallel wire bonding

Multiple parallel bond wires are preferred to reduce inductance and increase reliability. For two parallel bond wires with a spacing S between wires (figure 2b), the inductance of the pair is:

$$L_{pair} = \frac{L}{2} + \frac{M}{2} \quad (12)$$

where M is the mutual inductance and L is the self inductance.The detailled expressions for the mutual inductance M is given below:

$$M(nH) = \left\{\left[\sum_{i=1}^{3}\left(\sum_{j=1}^{3} a_{ij} R^j\right)\right] d^i\right\} Ln(S) + \left[\sum_{i=1}^{3}\left(\sum_{j=1}^{3} b_{ij} R^j\right)\right] \quad (13)$$

Table 2 lists the coefficients a_{ij} and b_{ij} (i = 1 to3 and j =1 to 3)

		j=1	j=2	j=3
A_{ij}	i=1	-5.654 10^{-12}	-3.331 10^{-8}	-9.972 10^{-7}
	i=2	-1.437 10^{-10}	6.724 10^{-6}	-3.585 10-5
	i=3	2.714 10^{-8}	-6.469 10^{-4}	0.0222
B_{ij}	i=1	-2.495 10^{-11}	1.999 10^{-7}	1.637 10^{-6}
	i=2	9.722 10^{-9}	-3.922 10^{-5}	2.333 10^{-4}
	i=3	9.136 10^{-7}	0.0036	-0.1546

Table 2: Coefficients b_{ij} and c_{ij} for the case of two parallel wire bonding.

III.3- Ribbon connection

The closed form expression for the case of ribbon is given below:

$$L(nH) = ALn(W) + B \quad (14)$$

where

$$A = 0,0028 - (1,621\ 10^{-4})\, l$$
$$B = B_1 \times (LnH)^2 + B_2 \times (LnH) + B_3$$
$$B_1 = B_{11} \times (l)^2 + B_{12} \times (l) + B_{13}$$
$$B_2 = B_{21} \times (l)^2 + B_{22} \times (l) + B_{23}$$
$$B_3 = B_{31} \times (l)^2 + B_{32} \times (l) + B_{33}$$

For the following set of parameters:

$$10 \le W(\mu m) \le 150$$
$$80 \le H(\mu m) \le 500$$
$$100 \le l(\mu m) \le 600$$

Table3 lists the coefficients b_{ij} (i =1 to3 and j = 1 to 3).

	ij	1	2	3	4
B_{ij}	1	1.12 10^{-8}	3.67 10^{-5}	0.0026	--
	2	-1.3 10^{-8}	4.34 10^{-4}	-0.0313	--
	3	1.35 10^{-9}	1.52 10^{-6}	3.11 10^{-4}	0.0028

Table 3: Coefficients B_{ij} for the inductance of a ribbon connection.

A good agreement (within 3%) is obtained between numerical solution and experimental results. In figure 5, for the case of of two parallel wires, the space S between two lines is taken equal to 400 µm. The calculated scattering parameters together with results measured using a WILTRON 360 network analyser are plotted in figure 7. Simulations have been carried out with HFSS (High Frequency Structure Simulator) **[8]**. We show in figure 8 and figure 9 a comparison between simulations results obtained using HFSS and measuread results for the case of one wire bonding and ribbon connection. The above formulas have been validated through extensive measurements performed in the 1 - 30 GHz frequency range. A good agreement (within 3%) is obtained with electromagnetic simulations as well as with experimental results.

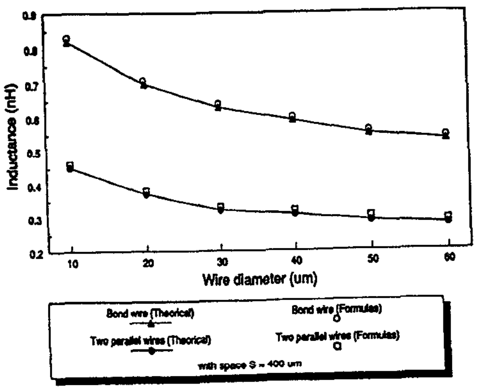


Figure 5: Comparison between analytical formulas and numerical results for one wire bonding and two parallel wire bonding.

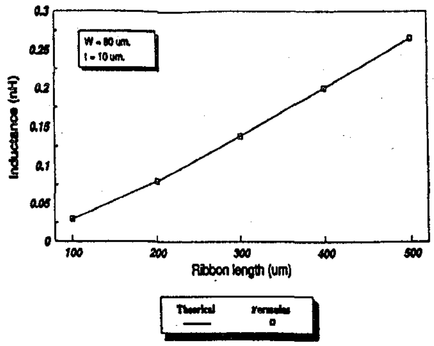
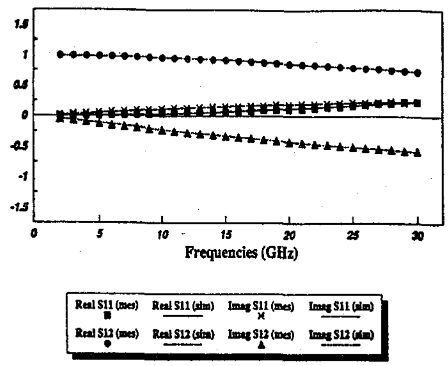
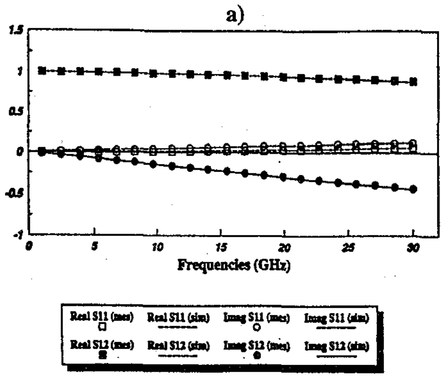


Figure 6: Comparison between analytical formulas and numerical results for ribbon connection (TAB).



a)



b)

Figure 7: Measured and simulated S11 and S12 parameters (f = 1 to 30 GHz).a)- One bonding wire. b)- Ribbon connection.

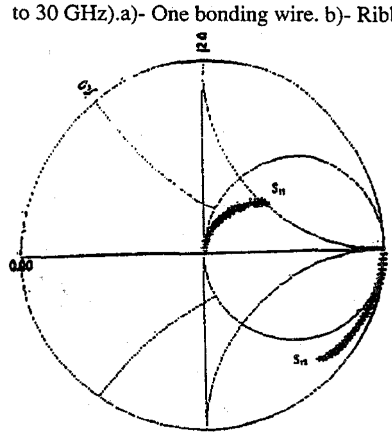


Figure 8: Scattering parameters measured (++) and simulated (----) using HFSS for one wire bonding.

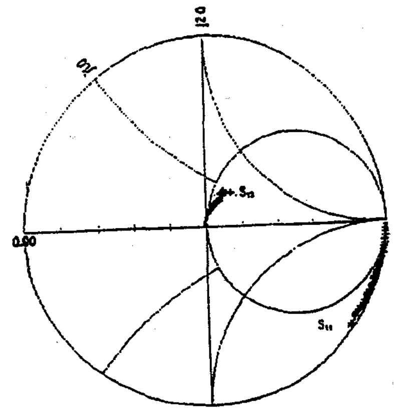


Figure 9: Scattering parameters measured (++) and simulated (----) using HFSS for ribbon connection.

IV- Conclusion

A simplified method to calculate the inductance and capacitance coefficients of short links (gold wire connections, vias, interconnection crossing and coupled lines) has been set up which allows to take into account precisely and easily the parasitic effects in circuit designs. Analytical formulas easy to use in CAD are derived from the numerical results using a least square method. The formulas have been shown to agree, with a precision in the order of 3%, with simulation results and with experimental results obtained on test boards in the frequency range 1-30 GHz. This formulas can be easily used in circuits simulation and optimization programs.

V- References

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