# EM Analysis of Inhomogeneous Layers Stack from the Wave Concept. Reduction of Substrate Couplings in BiCMOS Technology.

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*Abstract* — **This paper presents a new original full wave hybrid approach based on a wave concept formulation to analyze inhomogeneous layers stack with arbitrary doping profiles. To demonstrate capabilities of this approach simulation results are presented and successfully compared to published results and available software in the case of homogeneous multilayer BiCMOS typical structure with and without buried diffusions layers (BDL) for multi-level metallizations. To reduce epitaxial/substrate coupling noise, metallically grilled BDL with varying doping profiles are investigated and exhibit an isolation improvement of about 20 dB.**

## I. INTRODUCTION

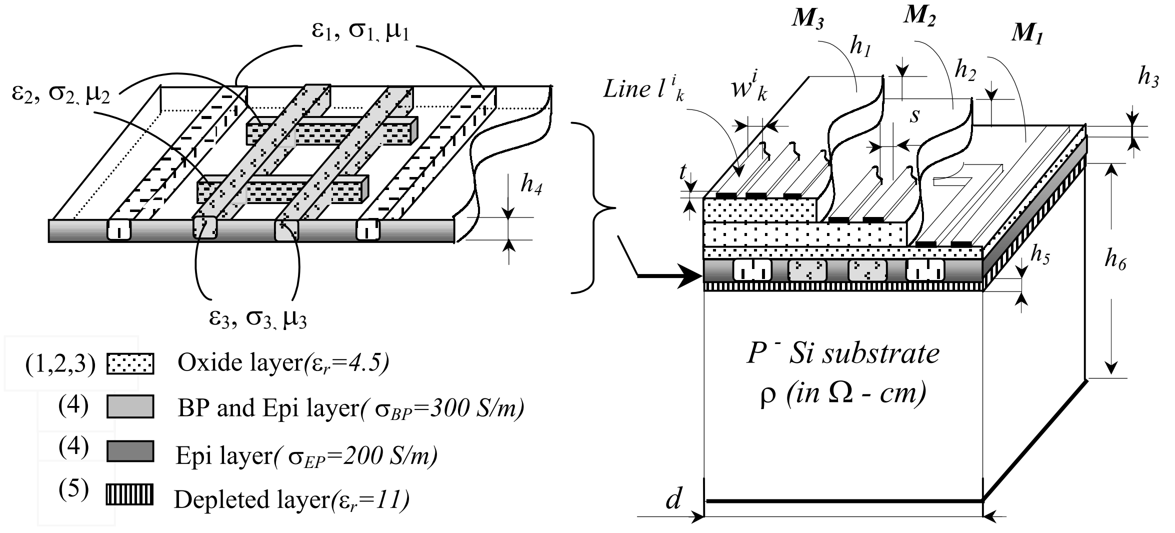
In BiCMOS technology, an increasing interest is directed towards including more and more functions in a single chip to meet the users' demands for dual-band or dual-mode (CDMA/AMPS) operating systems. Mixed-signal integration on a common Silicon substrate for high speed Analog/RF is faced with electromagnetic coupling effects of different origins. The lossy nature of highly doped Silicon substrate is of sensitive impact on the System-On-Chip (SOC) performances. On the other hand the presence of resistive buried diffusion layers which are required for active devices implantation is responsible of epitaxial currents giving rise to a significant increase in parasitic coupling noise. To suppress or reduce such disturbing couplings in Silicon RFIC, many methods have been used and several techniques were proposed. It's in this prospect that, for instance, Deep Trench Guard technology was used to improve isolation characteristics between sensitive noisy circuit blocks [1]. All these techniques result in inhomogeneous layers inserted in the substrate layers stack. Such recent configurations make the commonly used 2.5 D EM design tools meet their intrinsic limitations. By not elaborating global answer to this large class of problems, an adoc basis approach referring to parameterized equivalent circuit models is usually considered to overcome them. Numerous investigations dealing with analytical models deduced from intensive measurements or 3D simulations to model the frequency-variant characteristics of Silicon substrate have been published.

This work addresses the investigation of inhomogeneous buried diffusions and of patterned doping profiles inserted to reduce substrate/epitaxial coupling noise. Inhomogeneous layers stack with arbitrary doping profiles are analyzed from a full-wave analysis based on a new original hybrid method combining an integral wave concept based formulation to a local space finite-difference approach. The integral operators are built to traduce the boundary conditions in terms of incident and reflected waves on both sides of the metallized interfaces and of the inhomogeneous layers. In addition to their flexibility to handle complex geometry, the integral operators take advantage of both the spectral and spatial domain, the toggling between the two domains using an optimized Fast Mode Transform (FMT).

## II. THE FULL-WAVE ANALYSIS APPROACH.

The wave concept based formulation, to circumvent the inversion of the integral operator required in the MoM approach, computes the scattering parameters, using an iterative procedure involving planar exciting sources. In the following, for conciseness reasons only the main features concerning the modeling of buried diffusions with varying permittivity $\varepsilon_r(x,y)$ and permeability $\mu_r(x,y)$ will be presented. The incident and reflected waves, as function of the electromagnetic tangential fields ($\vec{E}$ and $\vec{J} = \vec{H} \wedge \vec{n}$, $\vec{n}$ being the outgoing unit normal vertor to the matching surface) in reference to a normalizing impedance Zr, are handled under their expansion (1) on an appropriate basis functions $(\vec{\Phi}_n)_{1 \le n \le N^2}$ chosen to eliminate steep gradients in the permittivity and permeability space derivatives.

$$\begin{cases} \vec{A}(x,y) = \dfrac{\vec{E}(x,y) + Z_r \vec{J}(x,y)}{2\sqrt{\mathrm{Real}(Z_r)}} = \displaystyle\sum_{n=1}^{N^2} \alpha_n \vec{\Phi}_n(x,y) \\ \vec{B}(x,y) = \dfrac{\vec{E}(x,y) - Z_r \vec{J}(x,y)}{2\sqrt{\mathrm{Real}(Z_r)}} = \displaystyle\sum_{n=1}^{N^2} \beta_n \vec{\Phi}_n(x,y) \end{cases} \quad (1)$$




(a) (b)

Fig.1. Typical BiCMOS structure with buried diffusions (b) – overview of the buried diffusions with different doping profiles (a)
*Nominal values range*: $h_1$ ,$h_2$ ,$h_3$=1-2 μm, $h_4$=1-3 μm, s=10-20 μm, w=5-10 μm, , $h_5$=1μm, $h_6$=300-500 μm and t=1 μm.

The differential operator relating the incident waves to the reflected waves on both sides of the inhomogeneous layers stems from the transverse operator built using local form of Maxwell equations relatively to the components lying on the inhomogeneous layers surface (see Fig.2). $\vec{E}$ and $\frac{\partial \vec{J}}{\partial z}$ on one hand, $\vec{J}$ and $\frac{\partial \vec{E}}{\partial z}$ on the other hand are respectively related by the transverse operators $L_E$ and $L_J$ which are given in relation (3) as follow, the subscripts 1 and 2 standing for side (1) and side (2) in Fig.2 :

$$\begin{cases} L_E(\vec{E}_1 + \vec{E}_2) = j\frac{\partial}{\partial z}\vec{J} \\ L_J(\vec{J}_1 + \vec{J}_2) = j\frac{\partial}{\partial z}\vec{E} \end{cases}, \ \vec{E}_k = \begin{vmatrix} E_x^k \\ E_y^k \end{vmatrix}, \vec{J}_k = \begin{vmatrix} J_x^k \\ J_y^k \end{vmatrix}, k = 1,2 \qquad (2)$$

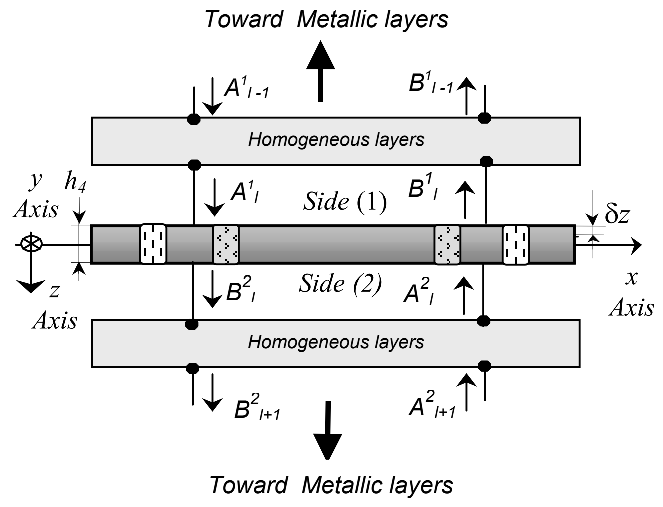



Fig.2 Cross section of the Inhomogeneous layer in Fig.1.a and definition of the incident and reflected waves.

$$L_E = \xi_o^{-1}\begin{vmatrix} k_o\varepsilon_r + k_o^{-1}\partial_y\mu_r^{-1}\partial_y & -k_o^{-1}\partial_y\mu_r^{-1}\partial_x \\ -k_o^{-1}\partial_x\mu_r^{-1}\partial_y & k_o\varepsilon_r + k_o^{-1}\partial_x\mu_r^{-1}\partial_x \end{vmatrix} \qquad (3)$$

$$L_J = \xi_o\begin{vmatrix} k_o\mu_r + k_o^{-1}\partial_x\varepsilon_r^{-1}\partial_x & k_o^{-1}\partial_x\varepsilon_r^{-1}\partial_y \\ k_o^{-1}\partial_y\varepsilon_r^{-1}\partial_x & k_o\mu_r + k_o^{-1}\partial_y\varepsilon_r^{-1}\partial_y \end{vmatrix}$$

where $\xi_o$ is the free medium normalizing impedance associated to the propagation constant $k_o$, $\partial_u$ designating the partial derivative operation $\partial/\partial u$, u = x, y. From relation (2), the scattering matrix for a layer of small thickness δz (see Fig.2.), relating the reflected waves to the incident ones can be expressed in the spatial domain as :

$$\begin{vmatrix} B_l^1(x, y) \\ B_l^2(x, y) \end{vmatrix} = \begin{vmatrix} \hat{S}_{11}^{\delta z} & \hat{S}_{12}^{\delta z} \\ \hat{S}_{12}^{\delta z} & \hat{S}_{22}^{\delta z} \end{vmatrix} \begin{vmatrix} A_l^1(x, y) \\ A_l^2(x, y) \end{vmatrix} \qquad (4)$$

with $w_l^k(x, y) = \begin{vmatrix} w_l^{kx}(x, y) \\ w_l^{ky}(x, y) \end{vmatrix}$, w = A, B - k = 1,2 .

and $\begin{cases} \hat{S}_{11}^{\delta z} = \hat{S}_{22}^{\delta z} = j\delta z \left\langle \varphi_u \left| \overline{L} \right| \varphi_v \right\rangle_{1 \le u, v \le N^2} \\ \hat{S}_{12}^{\delta z} = [I_d] - j\delta z \left\langle \varphi_u \left| \overset{+}{L} \right| \varphi_v \right\rangle_{1 \le u, v \le N^2} \end{cases}$ with $\begin{cases} \overline{L} = L_J - L_E \\ \overset{+}{L} = L_J + L_E \end{cases}$ (5)

$[I_d]$ being the identity matrix.

## III. Main Results and validation

### *A. Validation of the Modeling Approach*

Before dealing with the effects of buried diffusions with varying doping profiles on the isolation performances of the multilevel BiCMOS structure in Fig.1, the modeling approach previously introduced to compute the scattering matrix of an inhomogeneous layer of small thickness with

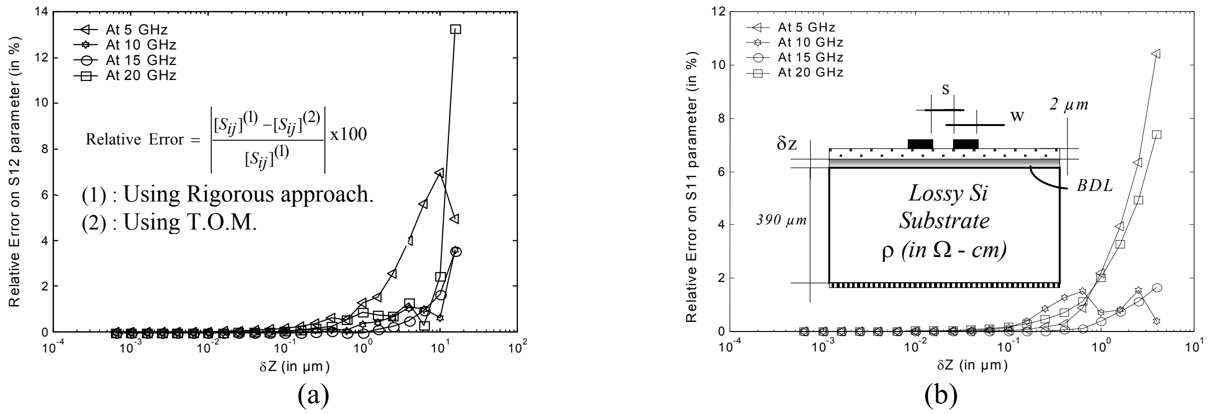



Fig.3 Relative error of the small thickness hypothesis for the modeling of arbitrary doping profile in comparison with a rigorous approach in the case of homogeneous layer stack against δz for two coupled strip lines (w=s=20 µm) .

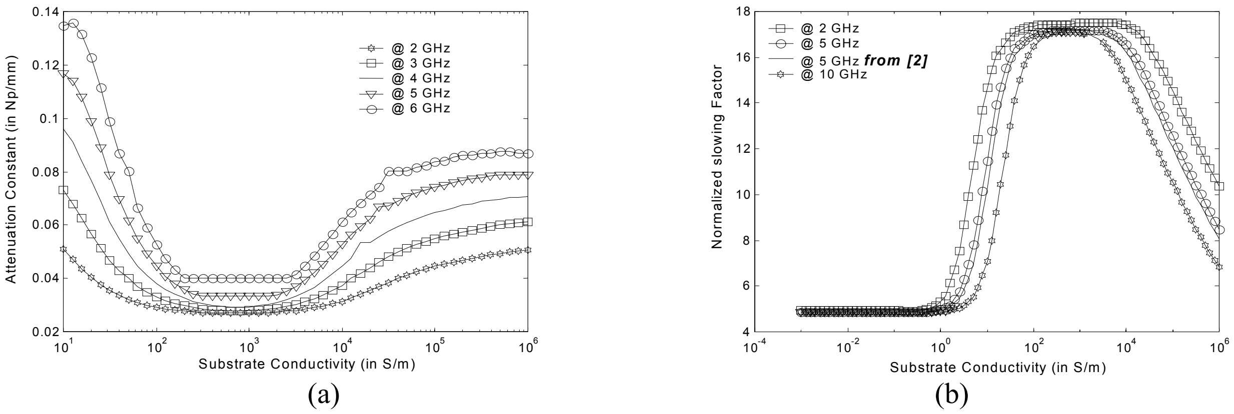



Fig.4 Effects of the substrate conductivity on the a single line attenuation constant (a) and the normalized slowing factor (b) for different frequencies without buried diffusions, comparison with [2] .

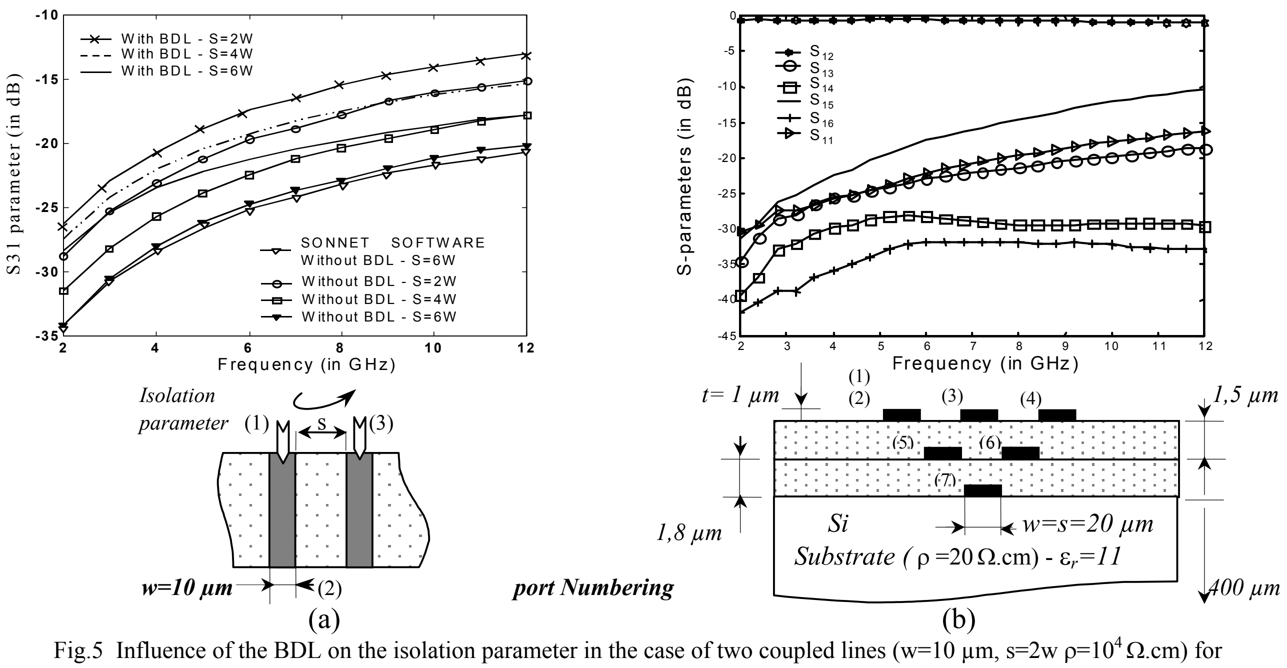
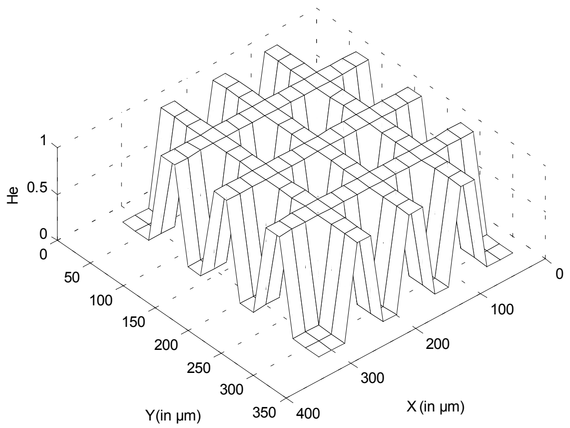



Fig.5 Influence of the BDL on the isolation parameter in the case of two coupled lines (w=10 µm, s=2w ρ=$10^4$ Ω.cm) for different line spacing (a) and multi-lines S-parameters for 3 metallisation levels (w=s=20 µm, , ρ=20 Ω.cm) from Fig.1 (b).

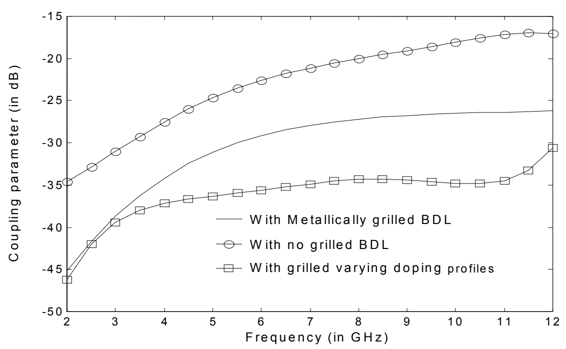
arbitrary doping profile is validated. Such approach based on the Transverse Operator Method (T.O.M), in assuming a small thickness hypothesis reduces significantly the penalizing memory requirement by not having to invert very big matrices usually involved in finite difference methods. For thicker inhomogeneous layers, a splitting into small layers to be cascaded for the computation of the resulting scattering matrix can be considered. Fig.3 shows a good agreement of the proposed approach in comparison with a rigorous analysis in the spectral domain in the case of homogeneous layers, with a relative error (see Fig.3.a) on the S-parameters of two coupled strip lines not exceeding 10% for a thickness $\delta z$ less or equal to 10 $\mu$m.

*B. Effects of grating Buried Diffusions layers on the Isolation performances.*

The resistive nature of the buried diffusions contributes to weaken the isolation capability as illustrated by Fig.5. The analysis of their effects on the propagation characteristics has demonstrated a more significant influence for higher substrate resistivity [3]. To improve the isolation performances of the typical structure shown in the insert of Fig.3.b in presence of BDL, we propose to consider doping profiles and metallic grills defined by the characterizing function He in Fig.6.a where $\sigma_{BDL}(x,y) = \sigma_{BDLn}He(x,y)$ , with $\varepsilon_{rBDL}(x,y)=\varepsilon_{rSi}$ He(x,y)+ $\varepsilon_{rOx}$[1-He(x,y)], where $\sigma_{BDLn}=400$ *S/m*, $\varepsilon_{rSi}=11$, $\varepsilon_{rOx}=4.5$, $\delta z=3$ $\mu m$). In Fig.6.b, metallically grilled BDL with varying doping profile exhibit significant reduction of the coupling effects in comparison with only metallically grilled BDL and with no grilled BDL. While a simple metallic grill on both sides of the BDL performs an isolation improvement of about 10 dB at 10 GHz, the insertion of varying doping profile allows an isolation enhancement of 20 dB.




(a)




(b)

Fig.6 Definition of the doping profile characteristic function He of the inhomogeneous layer (a) and Effects on the isolation parameter of the interruption of BDL (b) for two coupled lines.

## IV. CONCLUSION

From a new original hybrid approach using a wave concept based formulation, BDL in typical BiCMOS technology have been investigated. The Transverse Operator Method (T.O.M) have been used to model inhomogeneous layers with spatially varying doping profile under small thickness hypothesis. The small thickness hypothesis have been validated and a comparison with a rigorous approach in the spectral domain allowed to notice a relative error less than 10% for a thickness less or equal to 10 $\mu$m. Metallically Grilled BDL with varying doping profiles demonstrate isolation improvement of about 20 dB. Fig.7 shows that the wave concept based formulation CPU time ratio, unlike the MoM method [4] is not sensitive to the number of strip lines but depends only on the number of metallized levels.

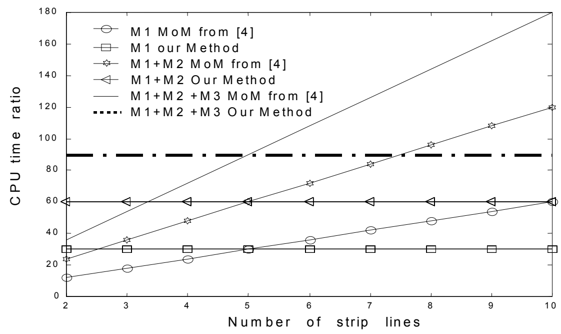



Fig.7 CPU time ratio comparison with the MoM method.

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