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Integrated Circuit Interconnect Lines on Lossy Silicon Substrate with Finite Element Method

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ABSTRACT
The silicon substrate has a significant effect on the inductance parameter of a lossy interconnect line on integrated circuit. It is essential to take this into account in determining the transmission line electrical parameters. In this paper, a new quasi-TEM capacitance and inductance analysis of multiconductor multilayer interconnects is successfully demonstrated using finite element method (FEM). We specifically illustrate the electrostatic modeling of single and coupled interconnected lines on a silicon-silicon oxide substrate. Also, we determine the quasi-static spectral for the potential distribution of the silicon-integrated circuit.
Keywords: Finite element method, capacitance, inductance, interconnect, silicon substrate.

I. Introduction

Due to the complexity of electromagnetic modeling, researchers and scientists always look for development of accurate and fast methods to extract the parameters of electronic interconnects and package structures. In recent years, we have observed a magnificent application and development in the complexity, density, and speed of operations of integrated circuits (ICs), multichip modules (MCMs), and printed circuit-boards (PCBs). For examples, MCMs are extensively used to reduce interconnection delay and crosstalk effects in complex electronic systems. Multiconductor transmission lines embedded in multilayered dielectric media are known as the basic interconnection units in ICs and MCMs, and have been characterized with the distributed circuit parameters such as capacitance C and inductance L matrices under quasi-TEM conditions. Also, these distributed circuit parameters are very important factor in the electrical behavior and performance of other microwave integrated circuits (MIC) and very large scale integration (VLSI) chips. Today, in the advances for fabrication of high speed integrated circuits, it is essential to examine the limitations due to the parasitic coupled mechanisms present in silicon-integrated circuit processes. To optimize electrical properties of IC interconnects such as minimization of the length of the interconnection lines, an adequate attention must be given to the geometrical size of their transverse cross sections; the estimation of the transmission line parameters requires being accurate for system design.

Multiconductor multilayered structures are essential for ICs, MCMs, and PCBs systems, due to the important effects on the transmission characteristics of high-speed signals. Also, the transmission lines effect on the IC interconnects become extremely important for the transmission behavior of interconnect lines on silicon oxide-silicon semiconducting substrate. The conducting silicon substrate causes capacitive and inductive coupling effects in the structure. Therefore, in this work, we apply the FEM for parameter extraction for electrostatic modeling of single and coupled interconnects lines on silicon-silicon oxide substrate.

Many researchers have presented various kinds of methods for solving the problem. These include equivalent source and measured equation of dielectric Green's function and boundary integral equation approach [1-4], CAD and quasi-static spectral domain [5-8], complex image method [9-10], quasti-stationary full-wave analysis and Fourier integral transformation [11], and conformal mapping method [12]. We illustrate that our method using FEM is suitable and effective as other methods for modeling of inhomogeneous quasi-static multiconductor interconnects in multilayered dielectric media.

In this work, we design of single and coupled interconnect lines on silicon-silicon oxide substrate using FEM. We focus on the calculation of the capacitance per unit length and inductance per unit length matrices of the single and coupled interconnects lines on silicon-silicon oxide substrate and we determine the quasi-static spectral for the potential distribution of the silicon-integrated circuit.

II. Results and Discussions

The models are designed in 2D using electrostatic environment in order to compare our results with some other available methods. In the boundary condition of the model's design, we use ground boundary which is zero potential ($V = 0$) for the shield. We use port condition for the conductors to

force the potential or current to one or zero depending on the setting.

We use FEM in our computations because it is suitable for the computation of electromagnetic fields in inhomogeneous media and it has high computation accuracy and fast computation speed.

In the following subsections, we demonstrate our work on modeling of the single and coupled interconnects lines on silicon-silicon dioxide **(**Si-SiO_2) substrate and we determine the quasi-static spectral for the potential distribution of the silicon-integrated circuit.

Our computation is focused on calculating calculation of the capacitance per unit length and inductance per unit length matrices of the transmission line interconnects on Si-SiO_2 substrate.

2.1 Single Interconnect Line on Si-SiO_2 Substrate

In this section, we illustrate the modeling of single interconnect line on silicon-silicon oxide substrate by focusing only on the calculation of the capacitance per unit length and inductance per unit length. Figure 1 shows the geometry of the model.

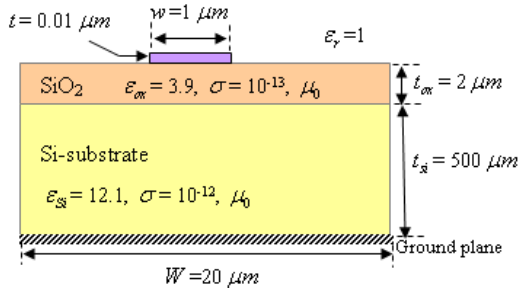

Figure 1 Cross-section of single interconnects line on Si-SiO_2 substrate.

The single line capacitance (C_s) per unit length placed on a stacked layer of the oxide and bulk silicon is given [13]:

$$C_s = \varepsilon_{ox}\left\{1.15\left(\frac{w}{t_{ox}}\right)+1.40\left(\frac{t}{t_{ox}}\right)^{0.222}\left(2+\frac{2w}{W}\right)+4.12\left(\frac{t}{t_{ox}}\right)^{0.728}\left(\frac{t_{ox}}{W}\right)\right\} \quad (1)$$

where $\varepsilon_{ox} = 3.9\times 8.855\times 10^{-14}(F/cm)$, w = width of the single conductor, t = thickness of the single conductor, W = width of the silicon-silicon oxide substrate, t_{si} =thickness of S_i layer, t_{ox} = thickness of SiO_2 layer .

The value of the single line capacitance (C_s) shown in Fig. 1 using eq. 1 is 5.33 x 10^{-11}F/m; furthermore, using our method the value of C_s is 4.43 x 10^{-11}F/m.

For lossless or low dielectric substrates, the single line inductance per unit length (L_s) can be directly and commonly computed from the equation 2 [14]:

$$L_s = \frac{\mu_0\varepsilon_0}{C_0} \quad , \quad (2)$$

where ε_0 = permittivity of free space $= \frac{1}{36\pi}\times 10^{-9} = 8.854\times 10^{-12}$ F/m, μ_o = permeability of free space or vacuum = 4 π × 10^{-7} = 12.6 × 10^{-7} H/m, L_s = inductance of the single transmission line, C_0 = the capacitance of the single transmission line when all dielectric constants are set equal to 1.

On the other hand, equation (2) is not accurate enough to be used for lossy lines, because the silicon substrate has high conductivity which results in the slow wave mode. In that mode, the storage of electric and magnetic energies is spatially separated. As a result, the integrated circuit (IC) interconnect model without the S_i semiconducting effect cannot be accepted for today's high-performance very large scale integration (VLSI) circuit designs any more [1].

Therefore, the inductance (L_s) model of a single interconnect line on silicon substrate is given by [15]:

$$L_s = \frac{\mu_0}{2\pi}\ln\left[\left(\frac{(t_{ox}+t_{si})}{0.59w}+1.1\right)-0.5+\sqrt{\left(\frac{(t_{ox}+t_{si})}{0.59w}+1.1\right)^2-1.05}\right] \quad (3)$$

where μ_o = permeability of free space or vacuum = 4 π × 10^{-7} = 12.6 × 10^{-7} H/m, t_{si} = thickness of S_i layer (substrate). Using equation (3) of the results for L_s = 1.488 μH

Table 1 shows the comparison results for the inductance per unit length (L_s) of the structure when the single interconnects line on silicon-silicon oxide substrate.

TABLE 1 Values of inductance per unit length (in μ H/m) for the single interconnects line on Si-SiO_2 substrate

Single line inductance per unit length (L_s)	Approach [1]	Experiment [16]	Equation 3
L_s	1.305	1.2505	1.488

Furthermore, Figures 2 through 4 show the potential distribution of the model with their variations in spectra peaks and full width half maximum (FWHM) from (x,y) = (0,502 μm) to (x,y) = (20 μm, 502 μm), from (x,y) = (0,500 μm) to (x,y) = (20 μm, 502 μm), from (x,y) = (0,0) to (x,y) =

(20 μm, 1500 μm), and from (x,y) = (0,0) to (x,y) = (20 μm, 1500 μm), respectively.

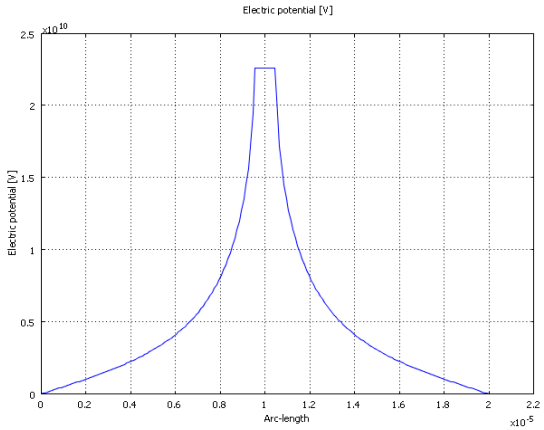

Figure 2 Potential distribution of single interconnect line on Si-SiO_2 substrate from (x,y) = (0,502 μm) to (x,y) = (20 μm, 502 μm).

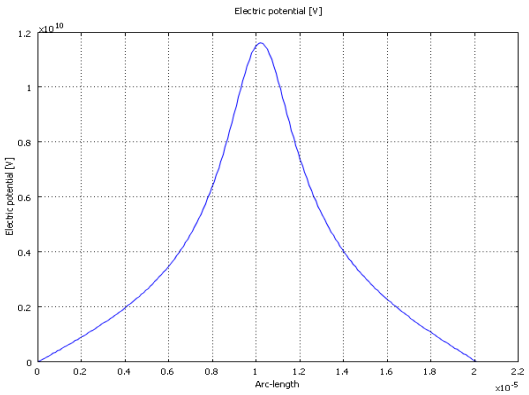

Figure 3 Potential distribution of single interconnect line on Si-SiO_2 de substrate from (x,y) = (0,500 μm) to (x,y) = (20 μm, 502 μm).

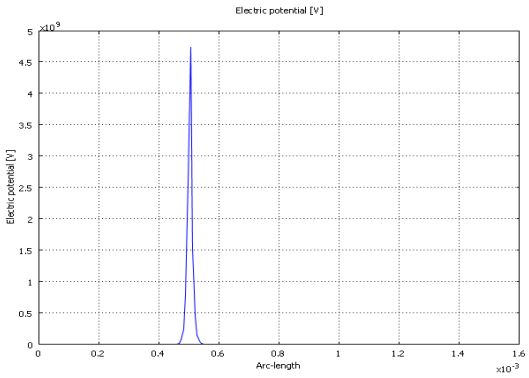

Figure 4 Potential distribution of single interconnect line on Si-SiO_2 substrate from (x,y) = (0,0) to (x,y) = (20 μm, 1500 μm).

Figure 5 shows the comparison analysis of potential distribution of the model with and without dielectric substrate. It observed that the peak value of electric potential is increased as the dielectric is placed in the substrate.

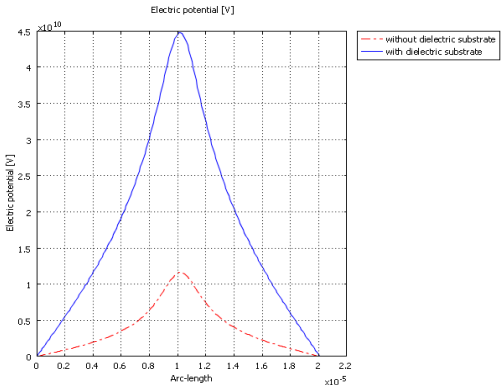

Figure 5 Comparison analysis of potential distribution of single interconnects line on Si-SiO_2 substrate from (x,y) = (0, 500 μm) to (x,y) = (20 μm, 502 μm).

2.2 Coupled Interconnect Lines on Si-SiO_2 Substrate

In this section, we demonstrate the electrostatic modeling of coupled interconnect lines on silicon-silicon oxide substrate by focusing only on the calculation of the inductance per unit length matrix. Figure 6 shows the geometry of the model with the parameters values.

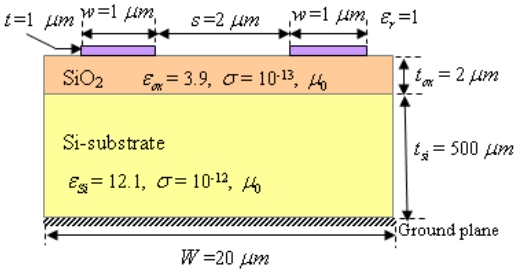

Figure 6 Cross-section of coupled interconnect lines on Si-SiO_2 substrate.

We use the results of our computation of capacitance to find inductance matrix.

The inductance matrix $[L]$ and capacitance per unit length matrix $[C]$ of multiconductor transmission lines system are commonly related for lossless or low lossy lines as [14]

$$[L] = \mu_o \varepsilon_o [C_o]^{-1}, \quad (4)$$

where

ε_0 = permittivity of free space $= \frac{1}{36\pi} \times 10^{-9} = 8.854 \times 10^{-12}$ F/m

μ_o = permeability of free space or vacuum = 4 $\pi \times 10^{-7}$ = 12.6 $\times 10^{-7}$ H/m

$[L]$ = inductance matrix.

$[C_o]^{-1}$ = the inverse matrix of the capacitance of the multiconductor transmission line when all dielectric constants are set equal to 1.

But, the silicon substrate lossy effect must be taken into account to calculate $[L]$ by using the effective dielectric constant μ_{reff} in equation (4) [1]:

$$\mu_{reff} = \frac{C_s L_s}{\mu_0 \varepsilon_0}, \quad \text{and} \tag{5}$$

$$[L] = \mu_o \varepsilon_o \mu_{reff} [C_o]^{-1} \quad . \tag{6}$$

Table 2 shows the comparison results for the self and mutual inductances of the structure when the coupled interconnect lines on silicon-silicon oxide substrate.

TABLE 2 Values of inductance matrix (in μ H/m) coefficients for the coupled interconnect lines on Si-SiO_2 substrate

Inductance matrix ($L_{ij} = L_{ji}$) and L_{ii}	Approach [1]	Our Work
Self inductance, $L_{11} = L_{22}$	1.877	1.841
Mutual inductance, $L_{12} = L_{21}$	0.278	0.253

Base on the table 2, we observe that FEM with COMSOL package is accurate and efficient for estimating the coupled transmission line parameters of interconnects. The results are compared with the previous work and found to be in good agreement. Additionally, Figures 7 through 9 show the potential distribution of the model with their variations in spectra peaks and full width half maximum (FWHM), from (x,y) = (0,502 μm) to (x,y) = (20 μm, 502 μm), from (x,y) = (0,500 μm) to (x,y) = (20 μm, 502 μm), and from (x,y) = (0,0) to (x,y) = (20 μm, 1500 μm), respectively.

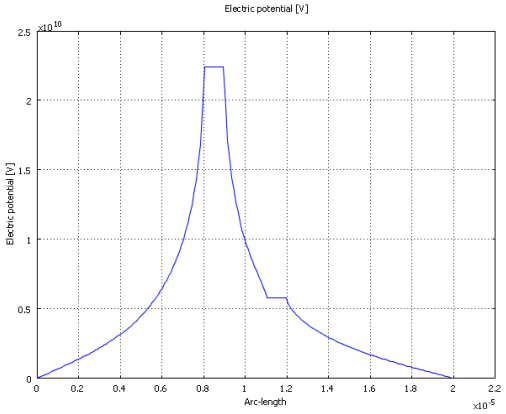

Figure 7 Potential distribution of coupled interconnect lines on silicon-silicon oxide substrate from (x,y) = (0,502 μm) to (x,y) = (20 μm, 502 μm).

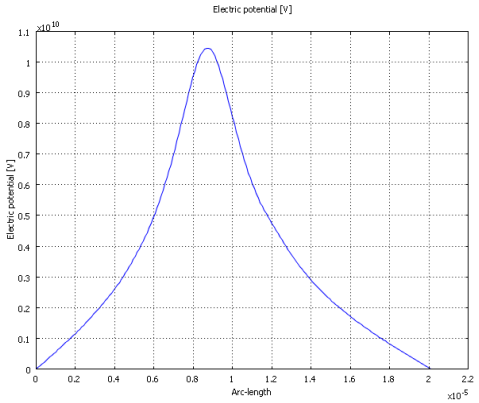

Figure 8 Potential distribution of coupled interconnects line on silicon-silicon oxide substrate from (x,y) = (0,500 μm) to (x,y) = (20 μm, 502 μm).

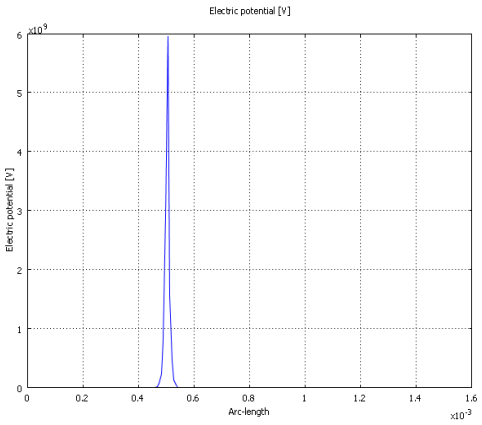

Figure 9 Potential distribution of coupled interconnect lines on silicon-silicon oxide substrate from (x,y) = (0,0) to (x,y) = (20 μm, 1500 μm).

III. Conclusion

In this article, we have presented the modeling of single and coupled interconnected lines on a silicon-silicon oxide substrate. The results obtained using FEM for the capacitance per unit length, and inductance per unit length agrees well with those found in the literature. In addition, we obtained for the models the potential distribution.

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