Simulation of Parasitic Interconnect Capacitance for Present and Future ICs

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Abstract. The performance of modern integrated circuits is often determined by interconnect wiring requirements. Moreover, continuous scaling of VLSI circuits leads to an increase in the influence of interconnects on system performance. It is desired therefore, to calculate accurately its parasitic components, particularly wiring capacitance. In order to recognize which one from the most popular empirical approaches gives the evaluation of the total capacitance that suits to the real capacitance of the interconnect line, the numerical simulations based on the numerical solving of Maxwell equations have been employed.

1 Introduction

Due to continually shrinking feature sizes, higher clock frequencies, and the simultaneous growth in complexity, the role of interconnections in determining circuit performance is growing in importance. This trend has led to the increasing dominance of interconnect delay over logic propagation delay – even with new metal technologies such as copper or new low-k dielectrics [1]. Additionally, increasingly large chip dimensions result in the longer interconnect lines, which give considerable contributions to the total power dissipation. Since the metallic interconnections are the crucial design issue for current and future generation of IC's, it is increasingly important to compute accurately all its parasitic components, particularly wiring capacitances. Their evaluation is a non-trivial task and it is a subject of many investigations [2],[3],[4]. There are two major approaches to calculate the parasitic capacitance. The first type is to use a numerical simulation, often based on Finite Difference Time Domain or on Finite Element Method [5],[6]. The numerical methods have good accuracy, however are too time-consuming, when applied to the whole integrated circuit. The second approach uses analytic formulations, derived from the equations of electromagnetism. These methods have a sufficient accuracy and a simulation speed, but they can be considered to simulate a few physical configurations, only. Empirical 2- and 3D capacitance models have been reported extensively in the literature. In order to recognize which one from the most popular approaches [7],[8],[9],[10] gives the evaluation of the total capacitance that suits to

the real capacitance of the interconnect line, the numerical simulations based on the numerical solving of Maxwell equations have been employed. The simulations were performed using the commercial software package OPERA [11], which uses finite element techniques to analyze the electromagnetic problems.

2 Electrical Models of On-chip Interconnections

Initially, interconnect has been modeled as a single lumped capacitance in the analysis of the performance of on-chip interconnects. Currently, at low frequency, the lumped RC models are used for high-resistance nets (Fig.1a) and capacitance models are used for less resistive interconnect [8],[12]. To represent the distributed nature of the wire, the interconnect is broken down into n smaller lumped section (Fig.1b). The simulation accuracy increases with increasing n . If the signal rise time is too short or the wire is very long, the inductance must also be included and an RLC network (Fig.1c), or the transmission line model (Fig.1d) must be used [13],[14]. The possible representations of interconnect line models include the Π , L and T networks.

Fig. 1. Models of interconnections. (a) Lumped RC line (b) Distributed RC line. (c) Distributed RLC line (d) Lossy transmission line.(n : number of distributed cells)

3 Analytical Models of Parasitic Interconnect Capacitance

An accurate model for the crossover capacitance is essential for estimating the interconnect circuit performance. To get an accurate interconnect capacitance electric field solvers (2D or 3D) should be used. It is, however, so huge task that it would take ages to estimate the capacitance of the whole chip. Therefore, various assumptions and approximations are used to get quick estimates. The empirical formulas, derived from the equations of electromagnetism have the sufficient accuracy and the simulation speed. The simplest equation for interconnect capacitance is given by.

$$C = \epsilon_0 \epsilon_{\text{SiO}_2} \frac{W}{H} L_{\text{Int}} \quad (1)$$

where H is the interlayer dielectric (ILD) thickness, ϵ_{SiO_2} is dielectric constant, ϵ_0 is the permittivity of free space, W and L_{int} are the width and the length of the interconnect respectively.

Fig. 2. Interconnect capacitance components

For interconnections in modern integrated circuits a large part of the capacitance comes from lateral coupling between adjacent wires placed on the same metal level and from fringing fields. This means that the values of extracted capacitance using simple parallel plate capacitor approximations are extremely inaccurate. In reality, the total interconnect capacitance is a sum of a few different capacitances resulting from the particular design of interconnect system and cannot be treated as the simple plane described by (1). As it is shown in Fig.2, one can distinguish the parallel plate capacitance component, C_P , the fringing field component, C_F , and lateral coupling capacitance component, C_L . It should be noted, that if the neighbor line switches in the opposite direction, the effective lateral capacitance doubles but if the neighbor line switches in the same direction the effective lateral capacitance equals to zero.

There are several approaches to identify the total capacitance C_{Total} , which use different models to define the components capacitances. The most popular of them are presented below. One of the first one was developed by Sarasvat [7]. He considered the structure shown in Fig.2 and described the component capacitances as follows:

$$C_P = \epsilon_{\text{ox}} \epsilon_0 \frac{W}{H} \quad (2)$$

$$C_L = \epsilon_{\text{ox}} \epsilon_0 \frac{T}{S} \quad (3)$$

$$C_{\text{Total}} = k(2C_P + 2C_L) \quad (4)$$

where T - line thickness, S - distance between two adjacent wires and k - the factor which takes into account the fringing fields, which value can be calculated using two-dimensional analysis of Dang and Shigyo [15].

Another model was presented by Sakurai [8] who derived a simple analytical formula for the total capacitance for symmetrical interlevel dielectric thickness. However, this formula takes into account a basic wire structure with one ground plane only. Because of the symmetrical nature of the interconnect structure considered in

this work, like is shown in Fig.2 the capacitance between wire and ground C_{vertical} and capacitance between adjustment wires $C_{\text{horizontal}}$ are multiplied by two.

$$C_{\text{vertical}} = \epsilon(1.15(\frac{W}{H}) + 2.80(\frac{T}{H})^{0.222}) \quad (5)$$

$$C_{\text{horizontal}} = \epsilon(0.03(\frac{W}{H}) + 0.83(\frac{T}{H}) - 0.07(\frac{T}{H})^{0.222})(\frac{S}{H})^{-1.34} \quad (6)$$

$$C_{\text{Total}} = 2C_{\text{vertical}} + 2C_{\text{horizontal}} \quad (7)$$

Chern in [9] presented a more complex crossover model for triple-level metal layer, which was the base for the formulas below:

$$C_{\text{vertical}} = \epsilon(\frac{W}{H} + 1.086(1 + 0.685e^{\frac{-T}{1.343S}} - 0.9964e^{\frac{-S}{1.421H}})(\frac{S}{S+2H})^{0.0476}(\frac{T}{H})^{0.337}) \quad (8)$$

$$C_{\text{horizontal}} = \epsilon(\frac{T}{S}(1 - 1.897e^{\frac{-H}{0.31S}} - \frac{-T}{2.474S} + 1.302e^{\frac{-H}{0.082S}} - 0.1292e^{\frac{-T}{1.421S}}) + 1.722(1 - 0.6548e^{\frac{-W}{0.3477H}})e^{\frac{-S}{0.0651H}}) \quad (9)$$

$$C_{\text{Total}} = 2C_{\text{vertical}} + 2C_{\text{horizontal}} \quad (10)$$

The last formula that will be presented here is taken from Wong work [10]. According to his model, the interconnect capacitance is described as:

$$C_{\text{vertical}} = \epsilon(\frac{W}{H} + 2.217(\frac{S}{S+0.702H})^{2.193} + 1.17(\frac{S}{S+1.510H})^{0.7642}(\frac{T}{T+4.532H})^{0.1204}) \quad (11)$$

$$C_{\text{horizontal}} = \epsilon(1.412\frac{T}{S}\exp(\frac{-4S}{S+8.014H}) + 2.3704(\frac{W}{W+0.3078S})^{0.25724}(\frac{H}{H+8.961S})^{0.7571}\exp(\frac{-2S}{S+6H})) \quad (12)$$

$$C_{\text{Total}} = 2C_{\text{vertical}} + 2C_{\text{horizontal}} \quad (13)$$

4 Numerical Model of Parasitic Interconnect Capacitance

In order to recognize which from the above formulas gives the evaluation of the total capacitance that suits to the real capacitance of the interconnect line, the numerical simulations based on the numerical solving of Maxwell equations have been employed. The simulations were performed using the Vector Field commercial software package OPERA [11], which uses finite element method to analyze the electromagnetic problems in 2D domain. This method divides the studied structure into sub-domains. Then, it is possible, with this tool, to fit any polygonal shape by choosing element shapes and sizes.

Fig. 3. Interconnect structure used in numerical capacitance calculation

The test interconnect structure is shown schematically in Fig.3. It contains three wires sandwiched between a two ground planes. Three copper lines are imbedded in a dielectric matrix (with the permittivity dependent on technology). The electric potentials and the currents have been fixed to arbitrary values. The cross-section dimension of investigated structure has been changed according to the technology. Typical views of the field distributions are represented in Figure 3. The shades give the intensity of the electric potential. This gives qualitative indications on the intensity of the coupling strengths. The software reports the total charge on the strip in Coulombs per meter. Since the total charge equals capacitance times voltage ($CV= Q$) then we can interpret the results from the software directly as capacitance per meter.

5 Comparison Between Analytical and Numerical Models

The total capacitance was calculated numerically and using four formulas mentioned above. Such a procedure has been repeated for several structures fabricated in 0.13, 0.10 and 0.05 μ m CMOS processes, which design parameters are collected in Table.1.

Table 1. Cross-section interconnect dimensions							
Technology	Layer	w	t	s	h	Eps	V
		[m]	[m]	[m]	[m]	-	[V]
130	1	1.46E-07	1.08E-07	1.54E-07	3.55E-07	2.00	1.20
	6	2.35E-06	2.00E-06	2.53E-06	6.67E-06	2.00	1.20
100	4	1.18E-07	2.04E-07	1.22E-07	3.55E-07	1.50	0.90
	7	2.22E-06	2.00E-06	4.98E-06	6.67E-06	1.50	0.90
50	7	1.20E-06	1.50E-06	1.20E-06	9.00E-07	1.50	0.60
	9	2.00E-06	2.50E-06	2.00E-06	1.40E-06	1.50	0.60

Eps – dielectric constant

The discrepancies between the total capacitance evaluation by means of analytical formulas and the OPERA simulations are shown in Table.2. The error used as the discrepancy measure is defined as follows:

$$Error = \frac{Analytical\ calculation - Numerical\ calculation}{Numerical\ calculation} 100\%.$$

(14)

Table 2. Error table of the analytical formulas compared with numerical simulator										
Tech.	Layer	OPERA	Mod.1	error	Mod.2	error	Mod.3	error	Mod.4	error
130	1	7.36E-14	7.84E-14	7%	8.26E-14	12%	1.16E-13	58%	3.94E-14	-46%
	6	7.39E-14	7.88E-14	7%	8.46E-14	14%	1.17E-13	58%	4.05E-14	-45%
100	4	7.63E-14	8.07E-14	6%	9.19E-14	20%	1.23E-13	61%	5.32E-14	-30%
	7	4.37E-14	4.56E-14	4%	5.23E-14	20%	7.51E-14	72%	1.95E-14	-55%
50	7	8.61E-14	9.22E-14	7%	1.06E-13	23%	1.48E-13	72%	6.86E-14	-20%
	9	8.93E-14	9.39E-14	5%	1.09E-13	22%	1.52E-13	70%	7.11E-14	-20%

where Mod.1 is the Chern [9] formula, Mod.2 is the Wong [10] formula and Mod.3 and Mod.4 are the Sakurai [8] and Sarasvat [7] approaches respectively. Based on this comparison one can judge that the empirical Chern’s formula that error value is less then 8% over a wide range of interconnect parameters can be treated as the more realistic one. It should be noted that the valid range of interconnect dimensions for this formula is [9]:

$$0.3 \leq \frac{W}{H} \leq 10; \quad 0.3 \leq \frac{H}{T} \leq 10$$

(15)

Fig. 4. Global interconnects capacitance versus technology node

Fig.4 shows the wiring capacitance per unit length C_0 calculated by Chern’s formula as a function of technology nodes. The calculations have been done for global interconnect with minimum cross-section dimensions (minimum wire pitch). It can be

noticed that the interconnect capacitance calculated for the present value of dielectric constant 3.6 remains almost the same, while the capacitance calculated for the values predicted by ITRS [1] tends to lessen.

6 Conclusion

The crossover parasitic interconnect capacitance is essential for estimating the interconnect circuit performance. To get an accurate interconnect capacitance electric field solvers should be used. Since it is too time-consuming, the empirical approximations derived from the equations of electromagnetism are used. Unfortunately these methods can be considered to simulate a few physical configurations, only. In order to recognize which from the most popular approaches gives the evaluation of the total capacitance that suits to the real capacitance of the considered interconnect structure (Fig.2), the numerical simulations based on the numerical solving of Maxwell equations have been employed. The presented comparison showed that only for the Chern formula the error value is less than 7% over a wide range of ITRS parameters. Therefore one can conclude that the Chern formula is the most realistic one for the considered interconnect structure.

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