DELAY AND INTERFERENCE IN INTERCONNECTS

Anca TOMESCU, Sorin ANTONIU, F.M.G. TOMESCU
Electrical Engineering Dept., POLITEHNICA University – Bucharest
Roxana Violeta MEGELEA

The delay and interference phenomena in integrated circuit interconnects are studied on a standard model in the *RC* approximation. The line parameters are evaluated by approximate analytical methods and a finite element numerical method for symmetric geometries and in the presence of process induced asymmetric structures.

INTRODUCTION

Integrated circuits are a pervasive presence in an extremely large number of modern equipment used in industry, medicine, home and consumer appliances, military, and many other fields. The natural miniaturisation trend coupled with the increase in their operating frequency make the integrated circuits more and more sensitive to delay and interference phenomena associated with internal interconnects. Such phenomena have been lately the subject of intense study [1,2,3 and the references mentioned there], to which the present paper proposes a contribution.

There are two main direction in the study of delays and interferences associated with integrated circuit interconnects: the simpler *RC* approximation, where the interconnects are modelled as *RC* transmission lines or by their approximate lumped parameter equivalent [4,5,6], and the complete transmission line approach [7,8,9].

The simple approach is considered here, using an elementary lumped parameter equivalent circuit of integrated circuit interconnects [1], whose elements are computed by approximate analytical methods and by a finite element numerical method for both symmetrical and asymmetrical configurations.

INTERCONNECT MODEL AND SIMPLIFYING ASSUMPTIONS

The standard interconnect structure used in the evaluation of interconnect delay and interference [1] is presented in fig. 1, where the symmetric configuration with interconnects of height h and width w are placed at horizontal distances $D = w$ or $a, b = w \pm \Delta w$ between them and at vertical distances $H = h$ or $c, d = h \pm \Delta h$ from upper and lower strata of similar interconnects, simulated as conducting planes. The lateral lines are considered as aggressor lines, to which the same signal is applied, and the central line is the victim line where an interference signal is detected.

The simplifying hypotheses are:

1°. The interconnect lines are very long as compared with the transverse dimensions;

2°. The media are linear and piece–wise homogeneous.

The signal delay on an interconnect line is roughly evaluated in relation with the time constant per unit length $\tau_{lin} = R_{lin} C_{lin}$, and the magnitude of the interference signal can be estimated as proportional to the $C_{inter-line} / C_{total}$ ratio.

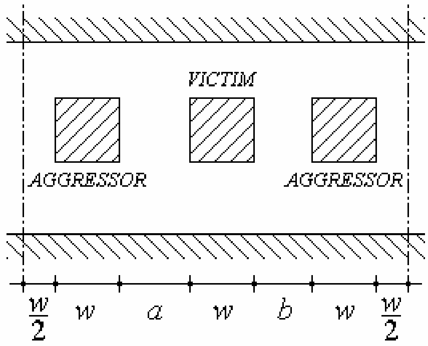

Fig. 1. Interconnect structure

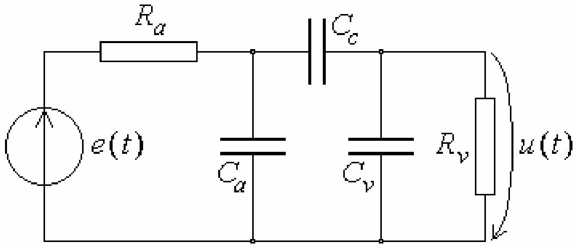

Fig. 2. Lumped circuit approximation

The simplest lumped circuit approximation of the interconnect system is presented in fig. 2, where R_a is the (resultant) aggressor line resistance, C_a is the (total) aggressor capacitance (to earth), C_c is the aggressor–victim capacitance, C_v is the (total) victim capacitance (to earth), R_v is the (total) victim resistance. A ramp signal $e(t)$ of amplitude V_{dd} and ramp duration T_r is applied at the initial moment to both aggressor lines, which induces on the victim line an interference signal

$$u = \begin{cases} \dfrac{R_v C_v V_{dd}}{\tau_0 T_r}\left(\tau_0 + \tau_1 e^{-t/\tau_1} - \tau_2 e^{-t/\tau_2}\right) & , \quad 0 \le t \le T_r \\ \dfrac{R_v C_v V_{dd}}{\tau_0 T_r}\left(\dfrac{1}{\tau_1}\left[e^{-t/\tau_1} - e^{-(t-T_r)/\tau_1}\right] - \dfrac{1}{\tau_2}\left[e^{-t/\tau_2} - e^{-(t-T_r)/\tau_2}\right]\right) & , \quad T_r \le t \end{cases}$$

where

$$\tau_0 = \sqrt{\left[R_a\left(C_a + C_c\right) + R_v\left(C_v + C_c\right)\right]^2 - 4 R_v R_a \left(C_v C_c + C_v C_a + C_c C_a\right)} \quad ,$$

$$\tau_{1,2} = \frac{2 R_v R_a \left(C_v C_c + C_v C_a + C_c C_a\right)}{R_a\left(C_a + C_c\right) + R_v\left(C_v + C_c\right) \pm \tau_0} \quad ,$$

$$R_a = R_{a1} || R_{a2} \quad , \quad C_a = C_{a1} || C_{a2} \quad , \quad C_c = C_{c1} || C_{c2} \quad .$$

The parameters of the interconnect lines are computed according to approximate formulae [1,11], according to analytical approximations (field line and equipotential surface approximations [12]), and by finite element numerical methods [13].

The interconnect parameters and their influence on delay and interference is evaluated starting from a symmetric reference configuration, where $w = h$.

The effects of horizontal and overall scaling is estimated for configurations with $(w/2, h)$ and $(w/2, h/2)$ values, respectively.

As well, the effects of manufacturing inaccuracy are evaluated by considering asymmetric configurations of constant pitch, where the horizontal distances between interconnects change to $w \pm 0.05\,w$ and $w \pm 0.1\,w$, respectively, or the vertical distances to upper/lower interconnect strata change to $h \pm 0.1\,h$ and $h \pm 0.2\,h$, respectively.

COMPUTATION OF THE INTERCONNECT PARAMETERS

The formula for the computation of the resistance per unit length in all cases is simply

$$R = \frac{\rho}{w\,h} \quad .$$

The approximate formulae for the computation of the capacitances per unit length are

$$C_{D,U} \cong \varepsilon \left[\frac{w}{x} + 1.086 \left(1 + 0.685\, e^{-h/1.343D} - 0.9964\, e^{-D/1.421x}\right) \left(\frac{D}{D+2x}\right)^{0.0476} \left(\frac{h}{x}\right)^{0.337} \right] \; ,$$

where $x = c$ for C_D, $x = d$ for C_U, $D = (a+b)/2$, and

$$C_{L,R} \cong \frac{\varepsilon\, h}{x} \Big[1 - 1.897\, e^{-H/0.31x + h/2.474x} + 1.302\, e^{-H/0.082x} - 0.1292\, e^{-h/1.421x} + $$
$$+ 1.722 \left(1 - 0.6548\, e^{-w/0.3477H}\right) e^{-x/0.651H} \Big] \; ,$$

where $x = a$ for C_L, $x = b$ for C_R, $H = (c+d)/2$.

The analytical formulae in the field line approximation are

$$C_L = \frac{h}{a} - \frac{4}{\pi}\left(1 - \frac{h}{a}\right) \; , \quad C_R = \frac{h}{b} + \frac{2}{\pi}\ln\frac{h}{b} \; , \quad C_U = C_D = 1 - \frac{1}{\pi}\left(1 - \frac{b}{h}\right) + \frac{2}{\pi}\ln\frac{a}{h} \; ,$$

$$C_{UL} = C_{DL} = 1 + \frac{2}{\pi}\ln\left(1 + \frac{\pi}{4}\right) + \frac{2}{\pi}\ln\frac{a}{h} \; , \quad C_{UR} = C_{DR} = 1 + + \frac{2}{\pi}\ln\frac{a}{h} - \frac{1}{\pi}\left(1 - \frac{b}{h}\right) \; .$$

in the case of horizontal asymmetry, where $a > w = h = c = d > b$, and

$$C_L = C_R = 1 + \frac{2}{\pi}\left(1 - \frac{d}{w}\right) + \frac{1}{\pi}\ln\frac{c}{w} \; , \quad C_U = \frac{w}{d} + \frac{4}{\pi}\ln\frac{w}{d} \; , \quad C_D = \frac{w}{c} - \frac{2}{\pi}\left(1 - \frac{w}{c}\right) \; ,$$

$$C_{UR} = C_{UL} = \frac{w}{d} + \frac{2}{\pi}\ln\left(\frac{\pi}{4} + 1\right)\frac{h}{d}\frac{w}{d} \; , \quad C_{DR} = C_{DL} = \frac{w}{d} + \frac{2}{\pi}\ln\left(\frac{\pi}{4} + 1\right)\frac{h}{c} - \frac{1}{\pi}\left(1 - \frac{w}{c}\right) \; .$$

in the case of vertical asymmetry, where $c > h = w = a = b > d$.

An analytical formula in the equipotential surface approximation is obtained for the total victim capacitance only as

$$C_{\sup} = \frac{B}{\ln\left[1 + \dfrac{a\,B}{h(1 + a/b) + w(a/c + a/d)}\right]} \; ,$$

where

$$B=\frac{\pi}{4}\left[\frac{3(a+d)-2\sqrt{ad}}{2(a-d)}\ln\frac{a}{d}+\frac{3(a+c)-2\sqrt{ac}}{2(a-c)}\ln\frac{a}{c}+\right.$$
$$\left.+\frac{3(b+d)-2\sqrt{bd}}{2(b-d)}\ln\frac{b}{d}+\frac{3(b+c)-2\sqrt{bc}}{2(b-c)}\ln\frac{b}{c}\right] \quad .$$

DELAY AND INTERFERENCE IN INTERCONNECTS

The capacitance per unit length values computed by the reference exponential formulae and by the field line approximation are in good (within 2%) agreement and show that the influence of horizontal asymmetry (within a constant $2w$ total interval) is opposite for lengthening/ shortening of distances, and result in practically no effect on the total victim capacitance per unit length. As well, in the same case, the total victim capacitance per unit length, as given by the reference exponential formulae, is better approached by the field line than the equipotential surface approximation.

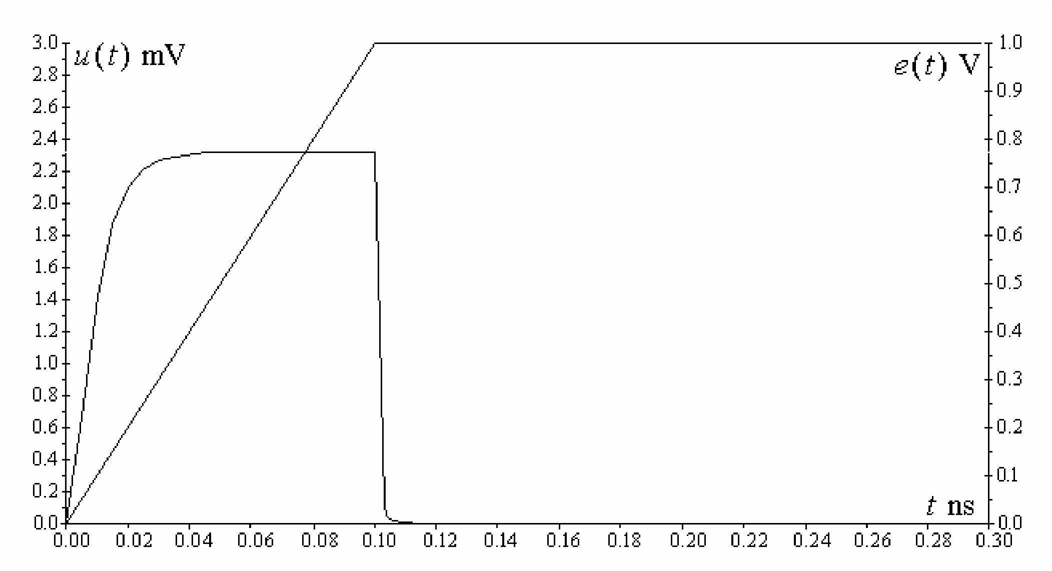

Fig. 3. Aggressor and interference signals

The capacitance values per unit length computed by reference exponential formulae and by the field line approximation show similar influences of vertical asymmetry (for a constant $2h$ total interval) but disagree in a one to two ratio. As well, in the same case, the total victim capacitance per unit length, as given by the exponential formulae, is better approached by the equipotential surface than the field line approximation.

The finite element numerical modelling is done on the model illustrated in fig 1, where the lateral limits at a $w/2$ distance from the aggressor lines were taken as equipotential. The system was treated as a complete system of conductors in an electrostatic field, with capacitance values (per unit length) computed accordingly.

The results of the numerical modelling do not agree well with both the exponential reference and the analytical approximate formulae. Even if this modelling was done on a rather coarse meshing, such a disagreement is a reason for more accurate studies of this type, aiming at refining the computation formulae of interconnect parameters.

The computations show that, as expected, the capacitances per unit length are not affected by overall down–scaling, while the resistance per unit length is increased, resulting in a proportional delay increase. As well, according to the same computations, the delay is practically unaffected (under 2.5%) by the assumed degree of vertical asymmetry and is even more insensitive (under 1%) to the assumed degree of horizontal asymmetry.

Finally, the interference signal induced on the victim line by a ramp signal of amplitude $V_{dd} = 1$ V and rise time $T_r = 0.1$ ns simultaneously applied to the aggressor lines was calculated for illustrative data: lines length $L = 0.5$ μm and parameters per unit length (equivalent values) $r_a = 2.8 \cdot 10^5\ \Omega/\text{m}$, $c_a = 6.58 \cdot 10^{-11}$ F/m, $c_c = 2.09 \cdot 10^{-11}$ F/m, $c_v = 3.29 \cdot 10^{-11}$ F/m, $r_v = 2.8 \cdot 10^5\ \Omega/\text{m}$.

The interference signal $u(t)$ is represented in fig. 3, and shows a reduced (approximately 2.3 mV) interference signal, restricted to the rise duration of the aggressor pulse.

CONCLUSIONS

A simple RC approximation of the delay time on interconnect lines and an approximate lumped element equivalent circuit for the evaluation of the interference between aggressor and victim interconnect lines were considered. The interconnect parameters per unit length were computed using different approximate analytical formulae and acceptable agreement was found between their results. However, some disagreement between the analytical and numerical modelling results suggests that there is room for improvement in the computation of interconnect parameters.

The unfavourable influence of down–scaling on the delay time was confirmed, which implies that down–scaling must be accompanied by a change to materials with improved constitutive parameters. The delay time was shown to be practically insensitive to manufacturing induced 10% asymmetry along the horizontal direction and 20% asymmetry along the vertical direction. The capacitive interference signal induced on a victim line by signals applied to lateral aggressor lines was found to be quite reduced in magnitude and practically limited to the duration of the applied signal time variation.

ACKNOWLEDGEMENTS

Thanks are due to the staff of the Numerical Methods Laboratory, and to colleagues in the Group of Theoretical Electrical Engineering of the Electrical Engineering Department, "Politehnica" University of Bucharest.

REFERENCES

1. R.H. Havemann, J.A. Hutchby, *High–Performance Interconnects*: *An Integration Overview*, Proc. IEEE, Vol.89, No.5, May 2001, pp. 586–601.
2. D. Sylvester, C. Hu, *Analytical Modeling and Characterization of Deep–Submicrometer Interconnect*, Proc. IEEE, Vol.89, No.5, May 2001, pp. 634–664.
3. R. Achar, M.S. Nakhala, *Simulation of High–Speed Interconnects*, Proc. IEEE, Vol.89, No.5, May 2001, pp. 693–728.
4. J. Van Bladel, *Electromagnetic Fields*, McGraw-Hill Book Company, New York, 1964.
5. Anca Tomescu, F.M.G. Tomescu, *Bazele electrotehnicii – Circuite electrice*, MatrixRom, Bucharest, 2002.
6. Anca Tomescu, F.M.G. Tomescu, R. Mãrculescu, *Bazele electrotehnicii – Câmp electromagnetic*, MatrixRom, Bucharest, 2002.

7. Matthew N.O. Sadiku, *Elements of Electromagnetics*, Saunders College Publishing, New York, 1989.
8. Simon Ramo, John R. Whinnery, Theodore Van Duzer, *Fields and Waves in Communication Electronics*, John Wiley & Sons, Inc., New York, 1994.
9. H.A. Haus, J.R. Melcher, *Electromagnetic Fields and Energy*, Prentice Hall, Englewood Cliffs, J.J., 1989.
10. Anca Tomescu, F.M.G. Tomescu, *Sisteme cu microunde*, MatrixRom, Bucharest, 2000.
11. Roxana–Violeta Megelea, *Întârzieri si interferente pe liniile de conexiune în circuite integrate*, Graduation thesis, Department of Electrical Engineering, Polytechnic University of Bucharest, 2003.
12. Anca Tomescu, F.M.G. Tomescu, *Bazele electrotehnicii – Sisteme electromagnetice* (*Lecture Notes*), Department of Electronics and Telecommunications, Polytechnic University of Bucharest, 1996.
13. Anca Tomescu, I.B.L. Tomescu, F.M.G. Tomescu, *Modelarea numericã a câmpului electro-magnetic*, MatrixRom, Bucharest, 2003.