Influence of Frequency-Dependent Characteristics on Deep Submicron Crosstalk Simulations

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Abstract

The SIA Roadmap shows a very aggressive drive to deep submicron designs. In this paper we discuss different approaches to the time domain simulation of crosstalk in deep submicron interconnects. We compare a technique based on frequency-independent parameters using a fast tool based on a distributed line model, against a new time domain simulator which can efficiently make use of the frequency dependent line parameters. The geometry of the line structures investigated is taken from the SIA Roadmap. This comparison constitutes an important contribution to the still open question if it is necessary to take the frequency dependence of line parameters in high-speed digital waveform simulations into account or not. The lines' cross sections are taken from the SIA Roadmap going from 250 nm down to 100 nm technology design.

1 Introduction

The SIA Roadmap [1,2] predicts a very aggressive path of technologies from 250 nm to 100 nm technology design and beyond. As a result, ASICs will have 5M gates per chip in 250 nm technology going to 430M gates per chip in 0.10 µm technology. So, one of the critical questions is: 'How does scaling in deep submicron affect the quality of signals on typical interconnects ?'

For the analysis of the line systems we first use an analog simulator which solves the transmission line equations derived from Maxwell's equations in the time domain. The resulting model takes into account wave propagation effects but neglects the frequency dependence of the line parameters. In order to demonstrate the influence of frequency-dependent parameters, we apply a second simulator which takes into account frequency dependent parameters and compare the results to those obtained from the first mentioned simulator.

The paper is organized as follows: In section 2, we describe the two simulation models which we used. In section 3, we show the line parameters of a specific 7-line system obtained from the SIA Roadmap. They are based on metal level 5 which is best suited for busses since it displays the lowest resistivity. In the following section 4, the simulation results of a 7-line system obtained by the two different simulation techniques are compared and discussed. Finally, section 5 summarizes the conclusions of our study.

2 Line Simulation with constant parameters

In order to simulate lossy coupled transmission lines which are characterized by *constant line parameters* we used the algorithm presented in [3]. This algorithm is based on the analytical solution of the transmission line equations for the lossless case, the well known solution of d‘Alembert. This closed form solution can be extended in a quite simple way in order to integrate the losses of the lines. To this end the line system is divided into a small number of sections and between these sections the resistances and conductances are connected. This model is very different from the commonly used lumped element model because it really starts from the partial differential equations and the partitioning of the lines is only necessary in order to distribute the losses along the lines. In contrast to that the lumped element model is gained from the partial differential transmission line equations by reducing them to ordinary differential equations which cannot describe wave propagation effects. In the next step, the wave propagation effects are then reintroduced by cascading several lumped segments while the number of the segments determines the quality of the approximation.

From a mathematical point of view the former model results in a very simple algorithm. The lossless parts of the model are described by recursive formulas, which means that the line voltages at the next time step are calculated from the values at the time step before. And the incorporation of the losses is simply a matrix multiplication.

This model can easily be implemented in a standard circuit simulator (e.g. in SPICE or a SPICE like simulator) as is demonstrated in [4]. Since this model does not require any numerical integration the algorithm is absolutely stable and very efficient. It provides very accurate results since it is based on the exact solution of the coupled partial differential equations. This tool has been used for the investigations presented in section 4.

For the simulation of transmission line systems with *frequency dependent parameters*, a tool described in detail in [6] was used for the investigations in section 4. The tool makes use of the well known solution of the telegraphers equations in the frequency domain. Then, each scalar transfer function resulting from that solution is approximated by fractional rational polynomials. These polynomials can be transformed back into the time domain in an analytically way so that the simulation algorithm finally results in an approach

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using recursive convolution.

It must be noted that a possible frequency dependence of on-chip line parameters is only resulting from two major physical reasons: First, there is the influence of conducting substrates and, second, proximity effects occur in the case of more than one return path. In contrast to the substrate, skin effects in the lines itself can *nearly always be neglected* since the cross-section dimensions of interconnects in the deep submicron area are in general much smaller or, in the worst case, in the same order as the skin-depth.

3 SIA - Roadmap Parameters

With the help of a sample geometry with five metal layers we examined how scaling in deep submicron affects the quality of signals. The geometric data for the different technologies have been extracted from the SIA Roadmap (cf. Tab. 1).

Technology	**250nm**	**180nm**	**150nm**	**130nm**	**100nm**
width µm	≥0.54	≥0.4	≥0.33	≥0.3	≥0.22
spacing µm	≥1.37	≥0.97	≥0.81	≥0.7	≥0.55
heigth µm	1.1	1.0	0.92	0.84	0.77
Dist. to subst. µm	7.25	6.49	6.08	5.65	5.35
epitaxy µm	2.0	2.0	2.0	2.0	1.0
substrate µm	400	400	400	400	400
clock Mhz	750	1200	1400	1600	2000
V_{DD} V	2.5	1.5	1.2	1.2	1.2

Tab. 1 Geometry data from SIA Roadmap for metal layer 5

In the first step, we extracted the transmission line parameters (resistance, inductance, capacitance and conductance per unit-length) for different substrate conductivities using a tool developed at our institute [5] which is based on two-dimensional quasi-analytical formulae. For random samples, the results have been verified with the help of a commercial finite-element field calculation program as well as with measurements.

Figures 1 to 3 show the frequency dependent line parameters C_{11} (capacitance to ground), L_{11} (self inductance) and R_{11} (resistance) of the middle line of a 7 line system in 100 nm technology for three different substrate conductivities.

Capacitance and inductance show quite a different behaviour. For the low conductivity substrate the inductance L_{11} is constant with the frequency whereas the capacitance C_{11} shows a sharp decrease for higher frequencies. For the high conductivity substrate we observe the opposite behaviour: C_{11} is nearly constant whereas L_{11} decreases with frequency. The same tendencies can be observed for the 250 nm technology.

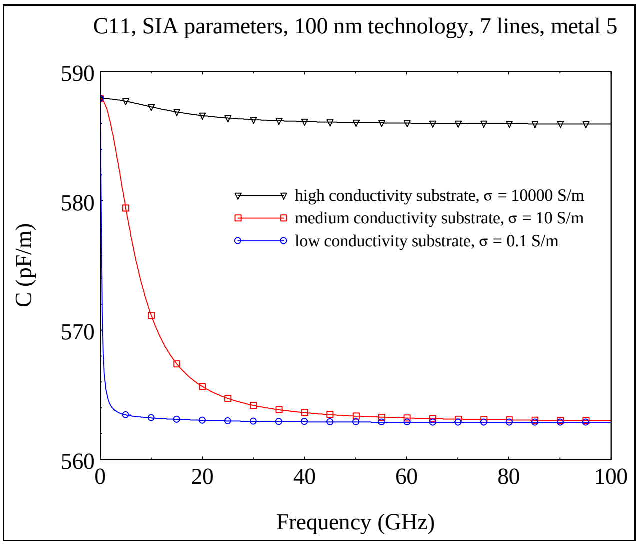

Fig. 1 self capacitance p.u.l. C_{11}, middle line (4th line)

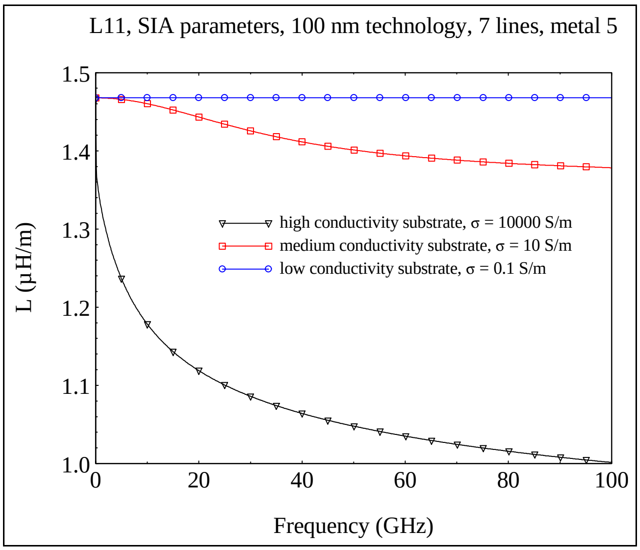

Fig. 2 self inductance p.u.l. L_{11}, middle line (4th line)

The reason is, that for low conductivities and low frequencies the substrate still acts as an conductor (=ground), i.e. the distance between line and ground is small: C_{11} is large. For high frequencies the substrate acts as an insulator, i.e. the electrical distance between line and ground (= return line) is now large and the capacitance becomes small. Since there is no skin-effect inside the substrate (and nearly no return current inside the substrate) inductance as well as resistance remains nearly constant. In the case of high substrate conductivity the substrate acts with respect to the electrical field almost as an ideal conductor and C_{11} is large and almost constant over the whole frequency range. Due to the high conductivity there is on the other hand a significant skin-effect inside the substrate. This leads to eddy currents (as well as to return currents) and therefore to increasing losses (i.e. an increasing R_{11}) as well as a decreasing inductance L_{11}.

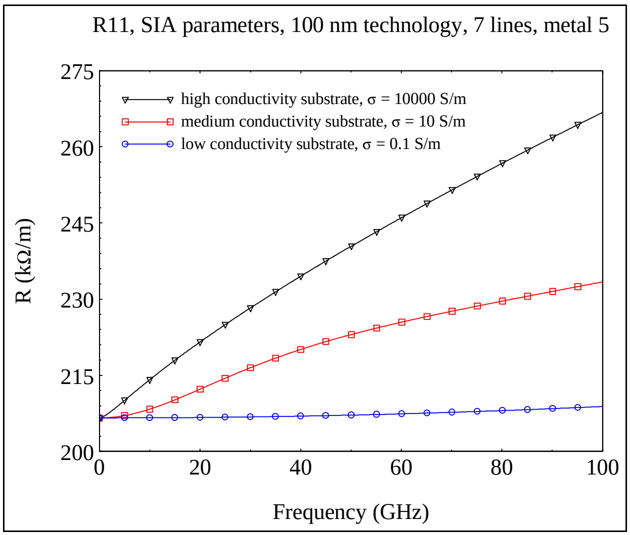

Fig. 3 resistance p.u.l. R_{11}, middle line (4th line)

Since the conductance is not of importance for the following considerations we abandon of its graphical presentation and discussion.

In the next section we will investigate the importance of these frequency dependent line characteristics.

4 Line Simulation Results

We start by examining the effects of signals propagating along a 7-line system located in metal 5 which shows the lowest resistivity. All lines except the 4th line (=victim line) are driven simultaneously by a ramp signal. Simulated is in each case the victim line far end signal. First we compare the simulation results of the tool using *constant* line parameters extracted at low (1 kHz) and high (10 GHz) frequencies for different substrate conductivities.

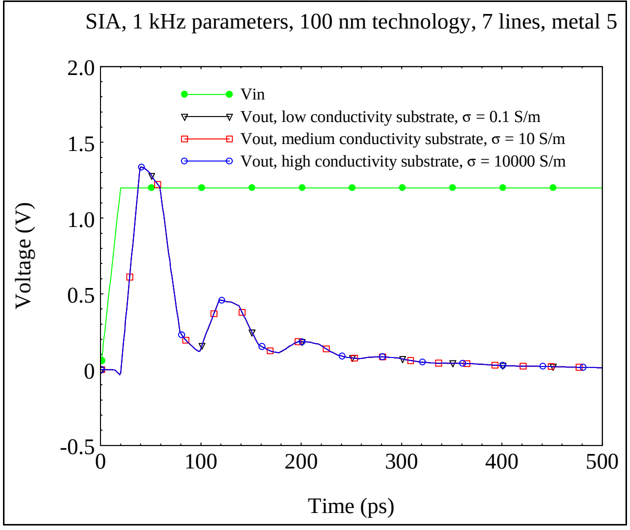

Fig. 4 victim line far end signal, different substrate conductivities

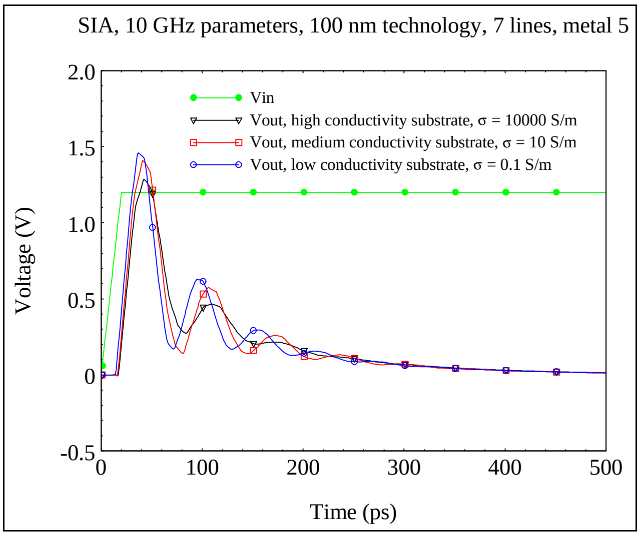

Fig. 5 victim line far end signal, different substrate conductivities

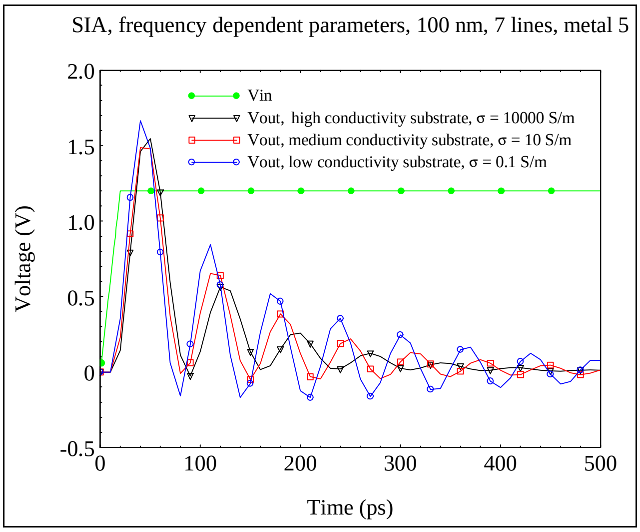

Fig. 6 victim line far end signal, different substrate conductivities

Figures 4 and 5 illustrate the far end noise of a 7-line system when using the simulator described in [3,4]. The parameters were extracted at low and high frequencies and for different substrate conductivities. Fig. 6 shows the results for the same line system obtained from the reference method (frequency-dependent simulation) of [6]. Figures 7 and 8 show the signal behaviour on the same line system, but for a 350 nm technology. Figure 9 depicts again the appropriate reference results. It can be clearly seen that it is not sufficient to perform the simulations with the line parameters extracted for the low frequency case. The difference between the low and high frequency case is much more distinct than for the 100 nm technology. Due to the line parameter characteristics as discussed in the previous section these effects can be observed especially for lower conductivity substrate. Since the computational effort for simulations with constant line parameters is significantly lower than for the frequency

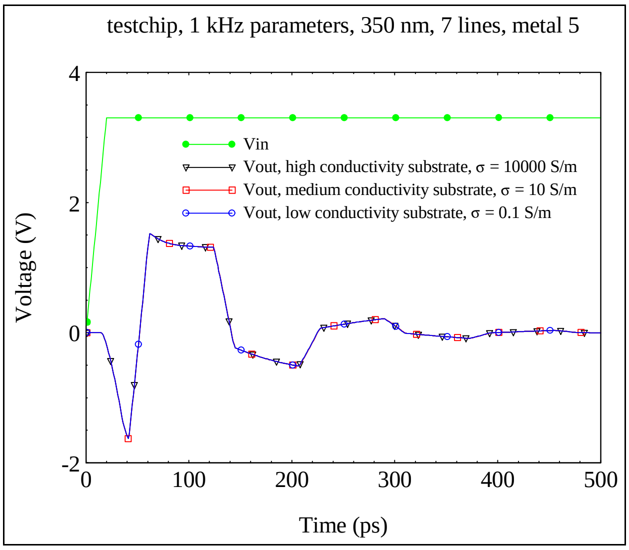

Fig. 7 victim line far end signal, different substrate conductivities

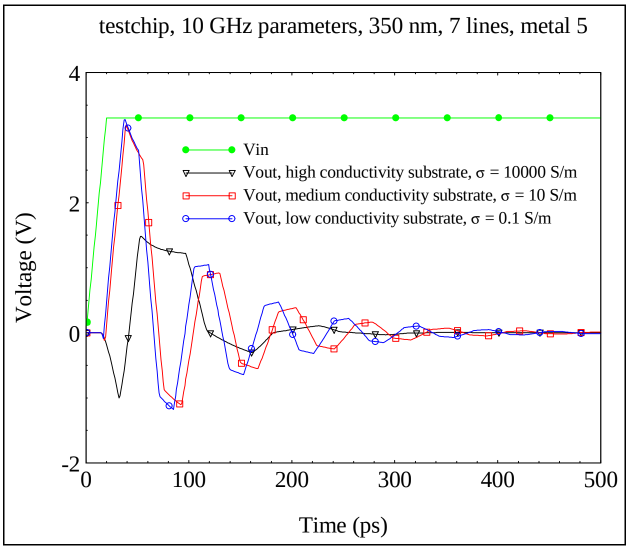

Fig. 8 victim line far end signal, different substrate conductivities

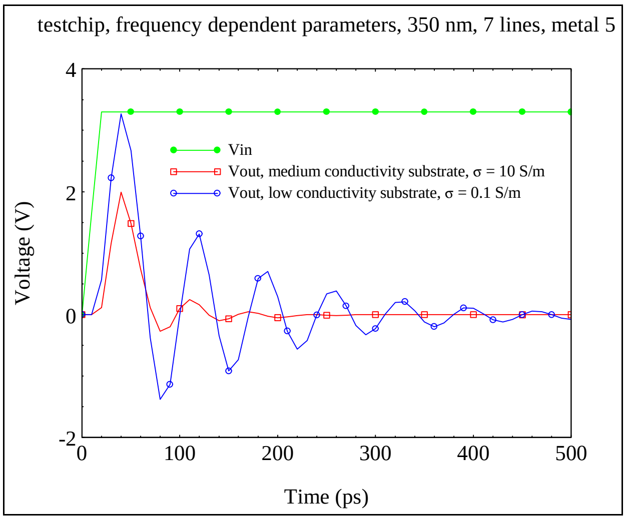

Fig. 9 victim line far end signal, different substrate conductivities

dependent approach, we came to the following recommodation when comparing figs. 5, 6 and figs. 8, 9, respectively: As long as the conductivity of the substrate is high enough the error introduced by using constant line parameters is usually negligible as long as the parameters are extracted for high frequencies.

For decreasing substrate conductivities we have to realize that considerable errors can arise no matter which frequency is used for the parameter extraction.

5 Conclusions

In this paper we have shown that the substrate conductivity severely affects a crosstalk in deep submicron interconnects. Frequency dependent simulation techniques are especially required for lower conductivity substrates. For higher conducting substrates it is often sufficient to use the very efficient simulation method described in [3] as long as the constant line parameters are extracted for high frequencies. Since in the deep submicron technologies usually very high substrate conductivities are used the last mentioned simple simulation method (i.e. using constant line parameters) can be recommended for crosstalk simulations.

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