MODELING THE OVERSHOOTING EFFECT OF MULTI-INPUT GATE IN NANOMETER TECHNOLOGIES*

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With the advent of nanometer age in digital circuits, the overshooting time becomes an important component of gate delay for CMOS logic gates. However, there has been little attention paid to the research of the overshooting effect for multi-input gate in nanometer technologies until now. Therefore, in this paper, an effective model considering the overshooting

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effect of multi-input gate is presented. The experimental results using 32-nm PTM model reflect that the proposed model is accurate within 3.6% error compared with SPICE simulation results.

Keywords: Nanometer age; multi-input gate; overshooting effect; gate delay.

1. Introduction

With digital integrated circuits entering nanometer age, the overshooting effect which is induced by input-to-output coupling capacitance strongly affects CMOS gate delay analysis, especially the static timing analysis. For traditional long channel transistors, the overshooting time is generally ignored because the coupling capacitance is small and the overshooting effect can usually be neglected.¹ However, with the scaling of gate feature sizes, the overshooting time is becoming equal to gate delay or even larger than that.² Therefore, the overshooting effect should be specially considered during the analysis of gate delay, otherwise the expression of gate delay would be inaccurate.

Traditional models of gate delay have been widely studied. Alpha-power law MOSFET model is applied to derive closed-form equation for evaluating the propagation delay in Ref. 3. An extension to the delay expression of Ref. 3 is presented in Ref. 4 to deal with the case of very lightly loaded inverter and/or slow input signals. However, neither Ref. 3 nor Ref. 4 takes consideration of the overshooting effect when analyzing gate delay. In the submicron range, the second-order effect which includes input slope and input-to-output coupling effect becomes the dominant factor. Although the overshooting effect which is induced by the input-to-output coupling effect is taken into account in the form of constant value or very simple expression in Refs. 5–9, there still have been few researchers focusing on the analysis of the overshooting effect in the level of nanometer technologies.

A detailed expression of the overshooting time for an inverter in nanometer technology is obtained by complete calculation and reasonable approximation in Refs. 2 and 10. However, the overshooting effect of multi-input gate is still not considered too much. Therefore, that effect is analyzed specifically in this paper. A basic two-input CMOS NOR gate is chosen as the research object and a practical model of CMOS NOR gate considering the overshooting effect is proposed. The specific expression of the overshooting time for the CMOS NOR gate is obtained from some reasonable calculation and approximation. Moreover, the proposed model is verified by comparing with SPICE simulation results using CMOS 32-nm PTM model.¹¹ The simulation results turn out that the accuracy of the proposed model is within 3.6% error. Furthermore, the proposed model can be easily extended to CMOS NAND gate according to the same principles.

The rest of this paper is composed of four sections as follows. First, the importance of the overshooting time is clarified in Sec. 2. Then the model of the overshooting effect for two-input NOR gate is proposed specifically in Sec. 3. After that, the

simulation results of the proposed model are shown in Sec. 4. At last the paper is concluded in Sec. 5.

2. Preliminaries

The overshooting time t_{ov} is now a key component of multi-input gate delay in nanometer regime with the scaling of process technology. Figure 1 shows a two-input CMOS NOR gate which takes into account gate-to-drain coupling capacitance and gate-to-source coupling capacitance. Figure 2 shows the output voltage V_{out} of the two-input NOR gate in the case that V_{in2} is connected to a falling signal and V_{in1} is directly connected to the ground by using CMOS 32-nm PTM model.¹¹ In Fig. 2, t_D is the gate delay time defined as the time elapses from $V_{in2} = 0.5V_{DD}$ to $V_{out} = 0.5V_{DD}$, t_{ov} is the overshooting time while the output voltage is below zero, t_r is the output voltage rise time from $t = t_{ov}$ to the time when $V_{out} = 0.5V_{DD}$, t_{in} is the transition time of input signal V_{in2} . Thus, the delay time t_D can be expressed as

$$t_D = t_{ov} + t_r - \frac{t_{in}}{2}. \quad (1)$$

Figure 3 shows the overshooting time t_{ov} and the gate delay time t_D of the two-input NOR gate in Fig. 1 for various nanometer process technologies from 90-nm technology to 22-nm technology. The input condition is that V_{in2} is connected to a falling signal and V_{in1} is connected to the ground. The transistor length L_n and L_p are the minimum feature size. The PMOS width is $W_P = 10L_P$ and the NMOS width is $W_N = 2W_P$. The load capacitance is $C_L = 0.01$ pF. The input transition time t_{in} of V_{in2} is 60 ps. In Fig. 3, both the overshooting time t_{ov} and the gate delay time t_D decrease with the scaling of process technology. On the contrary, the ratio value t_{ov}/t_D increases from 134.7% in 90 nm to 249.0% in 22 nm. Additionally, although t_{ov}/t_D will become small with the decrease of t_{in} , the overshooting time t_{ov} still

Fig. 1. CMOS NOR gate considering parastical coupling capacitance.

Fig. 2. Output voltage of CMOS NOR gate.

Fig. 3. Overshooting time t_{ov} and gate delay t_D with various process technologies.

occupies a large proportion of delay time t_D . Therefore, the overshooting effect of CMOS gate should be paid much more attention in nanometer regime. Modeling the overshooting effect of CMOS gate accurately can improve the accuracy of gate delay calculation.

3. Modeling the Overshooting Effect

In order to simplify the analysis of modeling the overshooting effect of CMOS NOR gate in Fig. 1, we discuss two different input conditions separately. The first input condition is that the falling signal is applied to V_{in1} and V_{in2} is connected to the ground. The second input condition is that $V_{in1} = 0$ and the falling signal is on terminal V_{in2} . Similar expressions can be obtained if the falling signals are changed to rising signals.

Fig. 4. CMOS NOR gate under the condition V_{in1} : High-Low V_{in2} : GND.

First, the analysis is given to the case as shown in Fig. 4, where the transistor M1 is not considered because the voltage of its four terminals are almost zero in the overshooting period. At the same time, M3 operates almost in the triode region, and is regarded as an active resistance during the overshooting effect period. The coupling capacitance C_{gd3} is not considered because the voltage between two nodes of the capacitance is almost constant during the overshooting effect period. Thus, the analysis for NOR is just similar to that for an inverter.

For the simplified NOR gate as shown in Fig. 4, the α -power MOSFET model³ is applied to calculate the current of the PMOS transistor. In order to simplify the numerical procedures, the drain current I_P of M4 is expressed with linear approximation as shown below:

$$I_{M4}(t_{ov}) = I_{D0} \left(\frac{|V_{GS}| - |V_{TPL}|}{V_{DD} - |V_{TPL}|} \right), \quad (2)$$

where I_{D0} is the drain current of a PMOS in saturation at $V_{GS} = V_{DS} = V_{DD}$ (V_{GS} and V_{DS} are the gate-source and drain-source voltages of the PMOS, respectively), V_{TPL} is the equivalent threshold voltage whose value is shown in Fig. 5. Actually it is shown in Fig. 5 that the linear approximation about drain current of M4 is almost identical as SPICE simulation result.

Therefore, the specific expression of the overshooting time t_{ov} is obtained using the method in Ref. 10. First, an initial expression of the overshooting time t_{ov} is calculated using the linear approximation of drain current for M4. The initial t_{ov} is expressed as¹⁰

$$t_{ov1} = t_{Vmin} - t_\gamma + \sqrt{\frac{2Q_1}{I_{D0}}(t_{in} - t_{TPL}) + t_\gamma^2}, \quad (3)$$

Fig. 5. The linear approximation for PMOS transistor drain current.

where

$$t_{\gamma} = \frac{1}{2} \left[t_{V_{\min}} - t_{TPL} - C_M \frac{V_{DD}}{t_{in}} \frac{t_{in} - t_{TPL}}{I_{D0}} \right]. \quad (4)$$

In Eqs. (3) and (4), $t_{V_{\min}}$ is the time when the output voltage is at its minimum. $t_{TPL} = \frac{|V_{TPL}|}{V_{DD}} t_{in}$. Also, Q_1 is the charge flowing out of the load capacitance C_L and C_{gd1} . In this paper, the values of $t_{V_{\min}}$ and Q_1 is obtained using the method similar to Ref. 10. Moreover, C_M is the coupling capacitance and in this paper C_M is expressed as

$$C_M = C_{gd2} + C_{gd4}. \quad (5)$$

The initial value of the overshooting time in the expression (3) is not accurate enough. Therefore, the initial t_{ov1} is substituted into the α -power MOSFET model to get a new drain current of M4 $I_P(t_{ov})$. Then the final overshooting time for the first input condition is expressed as

$$t_{ov1} = \frac{2Q_1}{C_M \frac{V_{DD}}{t_{in}} + I_P(t_{ov})} + t_{V_{\min}}. \quad (6)$$

Fig. 6. CMOS NOR gate under the condition V_{in1} : GND V_{in2} : High-Low.

For the other condition as shown in Fig. 6, the analysis becomes more complicated because the influence of the coupling capacitance C_{gs4} should also be considered. However, from $t = t_{ov}$ to $t = t_r$, M4 operates almost in the triode region, and is regarded as an active resistance. Then the NOR gate in Fig. 6 is simplified as shown in Fig. 7. Through various simulations in different conditions, we find that the overshooting time t_{ov2} of the simplified NOR gate in Fig. 7 is proportional to the overshooting time t_{ov1} of the simplified inverter in Fig. 4 as shown in Fig. 8. Thus, we

Fig. 7. Simplified CMOS NOR gate under the condition V_{in1} : GND V_{in2} : High-Low.

Fig. 8. The linear approximation for the overshooting time.

can obtain t_{ov2} referring to the value of t_{ov1} as shown below:

$$t_{ov2} = \lambda t_{ov1}. \quad (7)$$

Figures 9–11 are the simulation verifications of the expression (3) under different input signal transition times, transistor sizes and load capacitances. All these results are obtained from SPICE simulations. The length of NMOS and PMOS are $L_N = L_P = 40$ nm.

Figure 9 show the ratio of t_{ov2} to t_{ov1} under different input signal transition times. The load capacitance is $C_L = 0.01$ pF and the transistor size is $W_P/W_N = 0.8$ $\mu\text{m}/0.4$ μm . Figure 10 show the ratio of t_{ov2} to t_{ov1} under different NMOS widths. The PMOS' width is two times of NMOS' width. The input signal transition time is $t_{in} = 100$ ps and the load capacitance is $C_L = 0.02$ pF. Figure 11 show the ratio of t_{ov2} to t_{ov1} under different load capacitances. The input signal transition time is $t_{in} = 140$ ps and the transistor size is $W_P/W_N = 2.4$ $\mu\text{m}/1.2$ μm . Through the

Fig. 9. t_{ov2}/t_{ov1} versus different input signal transition time.

Fig. 10. t_{ov2}/t_{ov1} versus different gate sizes.

Fig. 11. t_{ov2}/t_{ov1} versus different capacitive loads.

verification as shown in Figs. 9–11, we can find that the ratio is almost constant and the value is approximately equal to 1.14. Therefore λ is about 1.14 for the 32-nm PTM model.¹¹ Based on other numerous simulations for various conditions, it is demonstrated that λ makes little change with the variation of input signal transition time, transistor size or capacitive load. Additionally, λ for different process technology can be obtained in the similar way.

4. Simulation Results of the Overshooting Time

Figures 12–14 show the overshooting time obtained from the proposed model and SPICE simulations for the first input condition with respect to various input signal transition times, transistor sizes and load capacitances using 32-nm PTM model.¹¹ Here the input signal transition time t_{in} varies from 40 to 120 ps. The NMOS' width

Fig. 12. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 4) with respect to various input signal transition times.

Fig. 13. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 4) with respect to various gate sizes.

Fig. 14. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 4) with respect to various capacitive loads.

W_N varies from 80 to 800 nm with $W_P = 2W_N$ and $L_P = L_N = 40$ nm. The load capacitance C_L varies from 0.01 to 0.1 pF and the length of PMOS and NMOS are $L_P = L_N = 40$ nm.

Simulation results in Figs. 12–14 show that the overshooting time obtained from the proposed model is very close to the SPICE simulation results. The error of the proposed model under the first input condition is less than 3.6%.

Furthermore, Figs. 15–17 show the overshooting time obtained from the proposed model and SPICE simulations for the second input condition with respect to

Fig. 15. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 7) with respect to various input signal transition times.

Fig. 16. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 7) with respect to various gate sizes.

Fig. 17. The overshooting time t_{ov} of the proposed model and SPICE simulation for CMOS NOR gate (Fig. 7) with respect to various capacitive loads.

various input signal transition times, transistor sizes and load capacitances using 32-nm PTM model.¹¹ All the simulation conditions are same as those of the first input condition. In addition, simulation results also show that the overshooting time obtained from the proposed model is close to the simulation results within 3.22% error.

5. Conclusion

With the advent of nanometer age in CMOS technology, the overshooting effect is more and more important during the analysis of gate delay. In this paper, we have modeled the overshooting effect caused in multi-input gates. The overshooting effect of CMOS NOR gate is modeled specifically. Additionally, simulation results show that the proposed model can correctly reflect the overshooting time of CMOS NOR gate compared to SPICE simulation results. Finally, the model of CMOS NOR gate considering the overshooting effect can also be easily extended to CMOS NAND gate according to the same principle.

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