Impact of Cu Local Interconnect on LSI Performance

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The effect of Cu local interconnect on intrinsic gate delay is analyzed. Beyond the 70-nm node, the intrinsic gate delay is limited by the local interconnect by taking account of electromigration in fine routings. Developments of materials and processes with improved electromigration for local interconnect are required.

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1. Introduction

An increase in clock frequency representative of LSI performance is attributed to a decrease in MOS transistor delay, which decreases by S^{-1} where S is the scaling factor ($S > 1$). In addition, the interconnect delay also affects the clock frequency. If all cross-sectional interconnect dimensions are scaled by the same factor as used for the transistors (ideal scaling), the delay time of global interconnect increases by $S^2 S_C^2$ where S_C is the scaling factor for the chip size ($S_C > 1$).¹⁾ Cu interconnect and low-k materials have been introduced to cope with the interconnect delay.^{2,3)} By contrast, the influence of the local interconnect delay on LSI performance has been disregarded due to its constant value in the ideal scaling. The current density of local interconnect increases by S , which needs an improved electromigration with scaling. However, the electromigration failure lifetime decreases with decreasing line width.⁴⁾ This means that the ideal scaling is inapplicable to the local interconnect. Thus, in this paper, new scaling scenarios for allowing the local interconnect to relax the current density with the same increase in packing density as that of transistors are proposed. The intrinsic gate delay, taking into account the local interconnect, is modeled and analyzed by numerical simulation.

2. Scaling Scenario

In the ideal scaling, all cross-sectional dimensions such as line width W_{INT} , line spacing W_{SP} , line thickness H_{INT} , and insulator thickness D_{FOX} decrease by the scaling factor S^1 , while the current density J_{INT} increases by S^1 . In order to relax the current density J_{INT} , new scenarios of quasi-ideal and constant- J scaling are proposed. The targets of the current density J_{INT} are $S^{1/2}$ and S^0 , respectively. Table 1 summarizes the effects of the above three scaling scenarios on local interconnect. The horizontal dimensions such as W_{INT} , W_{SP} , and line length L_{INT} are scaled by S^{-1} to improve the overall packing density by the factor S . In contrast, the vertical dimensions H_{INT} and D_{FOX} are reduced by the same factor, where H_{INT} meets the targeted current density.

3. Delay Modeling

The effect of local interconnect on signal delay is evaluated not by the product of routing resistance R_{INT} and routing capacitance C_{INT} , but by an equivalent circuit including transistors and local interconnect. Figure 1 shows an inverter-chain circuit that is a basic component of LSIs. The signal delay of the inverter-chain is evaluated using the equivalent circuit (Fig. 2), where R_{TRS} , C_D , and C_G represent the on-resistance, drain capacitance, and gate capacitance of MOS transistors,

Table 1 Scaling scenario for local interconnect.

Parameter	Ideal scaling	Quasi-ideal scaling	constant- J scaling
Current density, J	S^1	$S^{1/2}$	S^0
Line width, W_{INT}	S^{-1}	S^{-1}	S^{-1}
Line space, W_{SP}	S^{-1}	S^{-1}	S^{-1}
Line length, L_{INT}	S^{-1}	S^{-1}	S^{-1}
Line thickness, H_{INT}	S^{-1}	$S^{-1/2}$	S^0
Insulator thickness, D_{FOX}	S^{-1}	$S^{-1/2}$	S^0

Fig. 1 Inverter-chain circuit.

Fig. 2 Equivalent circuit.

Table 2 Simulation Parameters in nm.

Technology node		180	130	100	70	50	35
Ideal scaling	W_{INT}	250	180	140	100	70	50
	W_{SP}	250	180	140	100	70	50
	H_{INT}	300	216	168	120	84	60
	D_{FOX}	2500	1800	1400	1000	700	500
Quasi-ideal scaling	W_{INT}		180	140	100	70	50
	W_{SP}		180	140	100	70	50
	H_{INT}		255	224	190	159	134
	D_{FOX}		2121	1871	1581	1323	1118
Constant- J scaling	W_{INT}		180	140	100	70	50
	W_{SP}		180	140	100	70	50
	H_{INT}		300	300	300	300	300
	D_{FOX}		2500	2500	2500	2500	2500

Fig. 3 Interconnect model for signal delay evaluation.

respectively. Figure 3 gives an approximation for the signal delay by considering a negligible value of R_{INT} to R_{TRS} . Thus, the signal delay is simply evaluated by the product of R_{TRS} and parasitic capacitance ($C_{TRS}(= C_D + C_G) + C_{INT}$).

4. Results and Discussion

4.1 Routing capacitance

Figure 4 shows a local interconnect model to evaluate the routing capacitance. Routings INT_L and INT_R are arranged in parallel with routing INT_C . All the routings are formed above the silicon-substrate, and a field-oxide insulator with a thickness of D_{FOX} is in-between. The value of routing capacitance is obtained by using CLEVER,⁵⁾ a three-dimensional electrostatic field solver. Table 2 lists simulation parameters.

Dependence of routing capacitance per unit length on technology node X_{TN} , plotted in Fig. 5, is approximated by X_{TN}^0 , $X_{TN}^{-1/3}$, and $X_{TN}^{-2/3}$, for the ideal scaling (IS), quasi-ideal scaling (QS), and constant- J scaling (CS), respectively. Thus, the routing capacitance C_{INT} for IS, QS, and CS decreases by S^{-1} , $S^{-2/3}$, and $S^{-1/3}$, respectively, by considering both X_{TN} and line length L_{INT} decrease by S^{-1} . Therefore, relaxation of the current density increases the routing capacitance. The transistor capacitance C_{TRS} decreases by S^{-1} , thus suggesting that the routing capacitance C_{INT} will limit the intrinsic gate delay in shorter technology nodes.

4.2 Scaling of C_{TRS} and C_{INT}

A quantitative comparison between the transistor capacitance C_{TRS} and routing capacitance C_{INT} is graphed in Fig. 6, with the technology node X_{TN} of 180-nm chosen as a standard. The following device dimensions are expected from the

Fig. 4 Local interconnect model to evaluate routing capacitance.

Fig. 5 Routing capacitance per unit length vs. technology node for ideal scaling (IS), quasi-ideal scaling (QS), and constant- J scaling (CS).

references:^{6,7)} gate length L_G of 140 nm, gate width W_G of 700 nm, drain junction area of $350 \times 700 \text{ nm}^2$, effective gate oxide thickness of 3 nm, and typical interconnect length L_{INT} of 3,500 nm (around 20 times of X_{TN}). If constant- J scaling is applied, curves for C_{TRS} and C_{INT} intersect at the technology node of 70-nm. This means that the intrinsic gate delay is limited mainly by the local interconnect beyond the 70-nm node, and thus the constant- J scaling scenario should not be applied. Whereas the current density J_{INT} increases by $S^{1/2}$

Fig. 6 Parasitic capacitance C_{TRS} and C_{INT} vs. technology node for ideal scaling (IS), quasi-ideal scaling (QS), and constant- J scaling (CS). Interconnect capacitance is evaluated at L_{INT} of 20 times of X_{TN} .

and S^1 for QS and IS, respectively, developments of materials and processes with an increase in electromigration by more than $S^{1/2}$ are indispensable.

5. Conclusion

The influence of a Cu local interconnect on signal delay in connection with its electromigration has been analyzed.

The current densities in the ideal, quasi-ideal, and constant- J scaling scenarios decrease by S^1 , $S^{1/2}$, and S^0 , whereas the routing capacitances increase by S^{-1} , $S^{-2/3}$, and $S^{-1/3}$, respectively. Beyond the 70-nm node, the intrinsic gate delay is limited by the local interconnect in the constant- J scaling. This requires developments of interconnect materials and processes with improved electromigration.

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