Introduction

Historically, the delay of CMOS devices is benchmarked by the intrinsic delay $\frac{C_p}{V_{th}}$, where $C_p$ is the intrinsic gate-to-channel capacitance, and $V_{th}$ is the on-state drain current in saturation [1]. However, for a CMOS logic gate, the devices usually do not operate at the bias point which gives $I_{on}$. Instead, the whole trajectory of the device operating points matters. [2-5] studied the impact of different regions of device IV characteristics on the circuit delay performance and developed different effective current metrics for a better estimation of the circuit delay. On the other hand, at the device level, MOSFETs are benchmarked by characteristics such as on-state drain current ($I_{on}$), off-state drain current ($I_{off}$), DIBL, current booster factor ($k_v$), and so on. These device-level characteristics are often used as targets or specifications for technology development. Establishing the connection of these device-level targets with circuit-level performance is the subject of this paper. In this paper, we examine the impact of several device-level characteristics on circuit performance for various applications and we study the scaling trends.

Device Model and Circuit Simulation Methodology

As the devices are scaled down, short channel device suffers from poor gate electrostatics and other parasitic effects. High-k materials are introduced to improve the electrostatic control. Mobility and velocity boosters, e.g. strain, are introduced to keep $I_{on}$ boosted. At the device level, these improvements are revealed as lower subthreshold swing (SS), smaller DIBL, higher $k_v$, and so on. A new semi-empirical, physical IV model [6] is used which directly captures these behaviors. Parasitic capacitances are modeled following [7]. Parameters are characterized to fit devices characteristics at 32nm technology [8] (Fig. 1 & 2, fitting parameters in Table 1). Devices for 22nm technology are projected based on parameters and features listed in Table 2 [3]. Three different applications, i.e. high performance (HP) with low threshold voltage (LVT), low operational power (LoP) with standard threshold voltage (SVT) and low stand-by power (LstP) with high threshold voltage (HTV), are included. Circuit operation of 4-stage FO4 inverter chain and 2-input NOR chain of these devices are modeled with MASTAR [9]. Transient simulation with step input is done based on the IV model [6] and the parasitic capacitance models [7]. The average delay from the 50% input level to the 50% output level is extracted.

Impact of Device Characteristics on Circuit Speed

DIBL and $I_{on}$: During the switching process, the MOSFET that is turned on operates at the above-threshold region, where the gate voltage ($V_g$) is larger than the threshold voltage ($V_{th}$). Larger DIBL and $k_v$ can both result in a larger $I_{on}$. However, the origins of the larger $I_{on}$ are quite different and the impacts on IV characteristics are different. Compared with long channel devices, devices with higher DIBL have larger drain current under high $V_g$, with the same current at low $V_D$. However, devices with large $k_v$ have larger current booster ($I_{Iff}$) and higher current for both high and low $V_D$. Different combination of DIBL and $k_v$ may result in the same $I_{on}$ but different $I_{ff}$ behaviors. During switching as shown in Fig. 3, though $I_{on}$ is kept at the same level in both cases by adjusting $k_v$, the inverter chain built by devices with higher DIBL switches at a lower speed. This is universally true for HP, LoP and LstP cases. The LstP case is the most sensitive to DIBL, while HP is the least sensitive (Fig 3, 4). This is because when DIBL is changed by a fixed amount from the nominal value for all three cases, the absolute values of $I_{ff}$ [2], i.e., the current passed by the transistors averaged over the switching trajectory, are changed by a similar amount for all three cases (Fig 3). However, since LstP devices have the smallest nominal $I_{ff}$, the change in delay is the largest, as shown in Fig 3(c). To achieve a 10% speed-up of inverter-chain at 32 nm node, $k_v$ should be boosted to get a 15% higher $I_{on}$ for all three applications; or DIBL can be reduced to 80mV/V, 95mV/V and 110mV/V for HP, LoP and LstP, respectively (Fig 4).

$I_{off}$ and $V_{dd}$: $I_{off}$ and $V_{dd}$ are key factors for power consumption. $I_{off}$ is specifically important for static power, while $V_{dd}$ plays an important role for both static and dynamic power. Depending on the application, power and delay are traded off by engineering $V_{dd}$ (thus, $I_{off}$) and $V_{th}$. The $I_{off}$ drops exponentially with increasing $V_{dd}$ while $I_{on}$ drops proportionally to $(V_{dd}-V_{th})$. Among HP, LoP and LstP, delay is the most sensitive to $I_{off}$ and $V_{dd}$ for the LstP case, and the least sensitive for the HP case. This is because a change in $(V_{dd}-V_{th})$ results in a proportional change of $I_{off}$, but the percentage change is the most in LstP and the least in HP. At the 32nm technology, in order to achieve a 10% speed-up by trading-off power consumption, $I_{off}$ should be increased by 2.5x, 2x and 1.7x for HP, LoP and LstP, respectively; or $V_{dd}$ should be increased by 0.1V, 0.07V and 0.03V for HP, LoP and LstP, respectively (Fig 5).

More complex circuits: In NAND and NOR circuits, the stacked devices operate in the linear region most of the time [4]. For a balanced design with the same equivalent $I_{on}$ as inverters, NAND and NOR gates have larger gate capacitances, thus the switching trajectory of the parallel devices in NAND and NOR chains are further from the saturation point than the inverter chains since the devices are turned on more slowly. (Fig 3(d)). Thus, the delay is less sensitive to $I_{on}$. For the same balanced NMOS and PMOS, $I_{off}$ of NAND and NOR circuits [4] are much smaller than that of the inverter. The delay is more sensitive to DIBL, $I_{off}$ and $V_{dd}$, since the percentage change of $I_{off}$ due to a certain DIBL, $I_{off}$ and $V_{dd}$ is larger for NAND and NOR which have a smaller nominal $I_{on}$ than inverter. In general, the further the switching trajectory is from $I_{on}$, the more sensitive the delay is to DIBL, $V_{dd}$, $I_{off}$ and $V_{th}$.

Scaling Trends

As devices are scaled down, oxide thickness and channel length scaling are less and less effective. Increasing efforts are put into engineering current boosters and improving gate electrostatic control. With the nominal design parameters listed in Table 2, 22nm device delay performance are predicted as in Fig 7. For example, in HP application, the 22nm device with DIBL of 80mV/V and $I_{on}$ of 1.1$I_{on}$ has a 20% smaller switching delay than the nominal 32nm device for an FO4 inverter chain. To get a 17% speed-up over 32nm technology, devices have to fall into the upper-left regime above the dashed lines in the DIBL-$I_{on}$ contour map. The MASTAR program [9] is used to engineer physical device design, to meet the requirement as predicted by Fig 7. For HP (Fig 7(a)(d)), it is not practical to meet 17% speed-up requirement by solely engineering DIBL by aggressively designed junctions. Effort of boosting $I_{on}$ by continuing the engineering of strain or introducing high mobility material such as III-V/Ge, is necessary. This demand is more strict on complex circuit (such as NOR), than simple inverter chains. (Fig 7(d)). For LoP, switching to UTBSOI at 22nm can practically bring DIBL down to the regime which satisfies the scaling requirement of 17% speed-up per generation. For LstP, the requirement on DIBL improvement is further relaxed. Engineering the DIBL is more effective than introducing new channel material for LstP and LoP.

Conclusion

Starting from the device behavior model, we carefully analyze the impact of device characteristics on the circuit performance. The requirements of device characteristics are predicted as a guide for continuing technology scaling. With the prediction, UTBSOI structure is practical for LoP and LstP applications at 22nm technology. However, a combination of improved DIBL and transport enhancement is still necessary for HP application.
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Table 1 Key parameters for nominal cases at 32nm

<table>
<thead>
<tr>
<th>32nm</th>
<th>Physical meaning</th>
<th>NMOS HP/LoP/LstP</th>
<th>PMOS HP/LoP/LstP</th>
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<tr>
<td>$R_d$</td>
<td>Series resistance($\Omega$-µm)</td>
<td>350</td>
<td>350</td>
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<td>DIBL</td>
<td>Drain induced barrier lower (mV/V)</td>
<td>130</td>
<td>160</td>
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<td>$SS$</td>
<td>Subthreshold slope (mV/dec)</td>
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<td>98</td>
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<tr>
<td>$T_{on}$</td>
<td>Electric oxide thickness in inversion (nm)</td>
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<td>CPP</td>
<td>Contact poly pitch (nm)</td>
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<td>112</td>
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<tr>
<td>$I_{on}$</td>
<td>Channel length (nm)</td>
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<tr>
<td>$V_{DD}$</td>
<td>Supply voltage (V)</td>
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<tr>
<td>$I_{ON}$</td>
<td>On-state current (nA/µm)</td>
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<td>1257/1034/619</td>
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<td>$I_{OFF}$</td>
<td>Off-state current (nA/µm)</td>
<td>100/10/0.1</td>
<td>100/10/0.1</td>
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</tbody>
</table>

Figure 1 $I_{on}-V_{DD}$ characteristics in [8] is fitted. Lines = model. Symbols = experimental data [8].

Figure 2 $I_{off}-V_{DD}$. The model is fitted across a wide range of $I_{off}$. Lines = model. Symbols = experimental data [8].

Figure 3 Switching trajectories. $I_{on}$ in Case A and Case B are the same, while Case B has a degraded DIBL of 200mV/V. The absolute difference in $I_{off}$ are similar (~40A/m) for inverter chains with (a) HP, (b) LoP and (c) LstP devices.

Figure 6 NOR chain delay improvement contours on (a) DIBL-$I_{on}$ booster plane and (b) $I_{off}-V_{DD}$ plane, with 32nm HP devices. Delay of a NOR chain are more sensitive to DIBL, $I_{on}$ and $V_{DD}$ than that of an inverter chain (Fig 5(a) and Fig 6(a)).

Figure 7 Inverter chain delay improvement contours on DIBL-$I_{on}$ booster plane, with (a) HP inverter chain, (b) LoP inverter chain, (c) LstP inverter chain and (d) HP NOR chain, all at 22nm. The reference device is the nominal case at 32nm. To satisfy 17% speed-up over the parameter indicated by the axis. The dot-dashed line refers to 10% speed-up over the nominal case, indicated by the big white dot.

REFERENCES

[9] MASTAR  
http://public.itrs.net/models.html