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Current Drive Improvement by Enhanced Body Effect Factor Due to Finite Inversion Layer Thickness in Variable Threshold Voltage CMOS

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1. Introduction

It is well known that the electrical gate oxide thickness t_{ox_ele} increases due to the finite inversion layer thickness and the gate depletion, as shown in Fig. 1, and the current drive in the scaled MOSFETs with thin gate oxide is severely degraded [1]. As gate oxide is thinned, the effects of the inversion layer and gate depletion become dominant.

In this paper, we propose a new scheme for recovering the degraded current drive using variable threshold voltage CMOS (VTCMOS). Due to the inversion layer thickness and gate depletion, the body effect factor γ is enhanced. Therefore, the current drive is more improved when positive substrate bias is applied, thus recovering the degraded current drive. We adopt a fully-depleted (FD) SOI MOSFET in this study (Fig. 2), instead of a bulk MOSFET, because FD SOI has much clearer structural parameters that determine γ. Furthermore, forward bias range of the bulk device is limited by the built-in potential of pn-junction (~ 0.7 V), while in the FD SOI device much higher bias can be applied to substrate.

2. Concept for recovering the current drive

In VTCMOS, the threshold voltage (V_{th}) can be controlled by the substrate bias (V_{bs}) using the body effect [2-3]. While standby *off* current is kept small by setting V_{th} high, *on* current in the active mode can be enhanced by lowering V_{th} (Fig. 3). The threshold voltage shift is given by [4]

$$\Delta V_{th} = \gamma \left|\Delta V_{bs}\right|, \qquad (1)$$

where γ is the body effect factor which is analytically given by:

$$\gamma_{analytical} = \frac{C_d}{C_g} \cong 3\frac{t_{ox\_ele}}{l_d}, \qquad (2)$$

where C_d is depletion layer capacitance, C_g is gate capacitance, l_d is depletion layer width. In case of FD SOI, γ is written as

$$\gamma_{analytical} \cong \frac{C_{SOI}C_{BOX}}{C_g\left(C_{SOI}+C_{BOX}\right)} \cong \frac{3t_{ox\_ele}}{t_{SOI}+3t_{BOX}}, \qquad (3)$$

where C_{SOI} and C_{BOX} are capacitance of SOI and buried oxide, t_{SOI} and t_{BOX} are thickness of SOI and buried oxide, respectively. Since t_{ox_ele} includes the inversion layer effect and gate depletion effect, $\gamma_{analytical}$ is enhanced when these two effects are dominant. Fig. 4 compares the values of $\gamma_{analytical}$ with and without these two effects using eq. (3). It is assumed that the sum of inversion layer and gate depletion thickness is 1 nm. The physical oxide thickness t_{ox} is 1.8 nm, and the other structural parameters are also shown in Fig. 4. It is clearly seen that the body effect is enhanced by the finite inversion layer thickness and gate depletion. Therefore, when positive bias is applied to substrate, much more enhancement in current drive is expected.

3. Measurement

The effect of enhanced γ is examined by measuring n-type SOI MOSFETs [5] with two different t_{ox}; 1.8 nm and 3.5 nm. Both gate length (L_g) and width (W_g) are 10 μm. Device parameters are summarized in Table I. Fig. 5 shows the V_{bs} dependence of V_{th}. When the sum of inversion layer and gate depletion thickness is assumed to be 1 nm, the $\gamma_{analytical}$ and measured γ are in excellent agreement. This clearly demonstrates that γ is enhanced by the inversion layer and gate depletion. In the device with t_{ox} = 1.8 nm at V_d = 1 V and $V_g = V_{th0} + 0.8$ V (V_{th0} is V_{th} at V_{bs} = 0 V), the current drive (I_{on}) is improved by 15% at applying V_{bs} = 2 V (relative to the current at V_{bs} = 0 V) and by 32% at V_{bs} = 4 V.

4. Simulation

In order to estimate the prospects for scaled physical t_{ox}, we performed two-dimensional device simulation [6]. Fig. 6 shows the physical t_{ox} dependence of current drive. L_g, t_{SOI}, and t_{BOX} are fixed and the values are summarized in Table I. Acceptor density in SOI (N_a) is set to 3×10^{17} cm^{-3}. The substrate is p-type and doping density is 5×10^{17} cm^{-3}. When the effects of inversion layer and gate depletion are ignored, I_{on} is almost inversely proportional to physical t_{ox}. However, when these two effects are taken into account, the degradation of current drive is observed. When V_{bs} of 2 V or 4 V is applied, I_{on} is clearly improved and the recovery of the degraded current drive is obtained. Measured results are also plotted in Fig. 6, and they are in good agreement with simulated results. However, the recovery rate of current drive seems to decrease with scaling t_{ox} in Fig. 6. This is because γ is reduced with scaling t_{ox} according to eq. (3) when t_{SOI} and t_{BOX} are set constant.

In order to take advantage of this scheme in scaled t_{ox}, t_{SOI} and t_{BOX} should be also properly scaled. Fig. 7 shows the simulation results with scaled t_{SOI} and t_{BOX} at the fixed ratio with t_{ox}, and Fig. 8 shows physical t_{ox} dependence of I_{on} enhancement rate and γ. I_{on} enhancement rate increases with scaling t_{ox}. This is because the effect of inversion layer and gate depletion becomes dominant and γ increases with scaling t_{ox}. Therefore, this scheme is quite effective in scaled MOSFETs.

5. Conclusion

We propose a new scheme for recovering the degraded current drive due to finite inversion layer thickness and gate depletion, using VTCMOS. This scheme utilizes the body effect, which is enhanced by the effects of inversion layer and gate depletion. It is revealed that if thickness scaling is properly achieved, the effectiveness of this scheme will increase in scaled MOSFETs.

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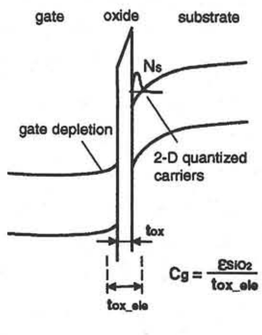

Fig. 1. Schematic band diagram to show the increase in electrical oxide thickness.

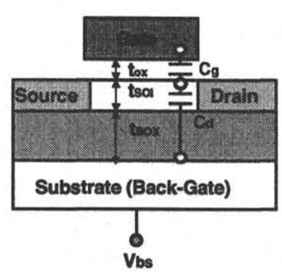

Fig. 2. Structure of an FD SOI MOSFET. In FD SOI, C_d corresponds to the series connection of C_{SOI} and C_{BOX}.

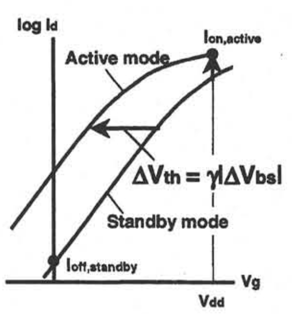

Fig. 3. Principle of VTCMOS. Active *on* current is enhanced by lowering V_{th},, while standby *off* current is kept low.

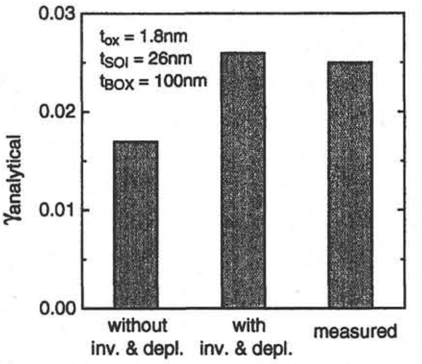

Fig. 4. Enhancement of $\gamma_{analytical}$ due to inversion layer and gate depletion. It is assumed the sum of inversion layer and gate depletion thickness is 1 nm, i.e., $t_{ox\_ele} = t_{ox} + 1$ nm. γ is enhanced from 0.017 to 0.026. Measured γ is also shown.

Table I. Device parameters of the measured and simulated FD SOI MOSFETs.

Lg	10 μm
Wg	10 μm
tox	1.8 nm / 3.5 nm
tSOI	26 nm
tBOX	100 nm
γanalytical	0.026 / 0.041
γmeasured	0.025 / 0.040

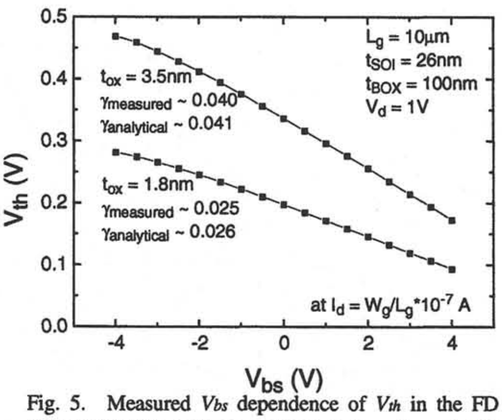

Fig. 5. Measured V_{bs} dependence of V_{th} in the FD SOI MOSFETs with two different t_{ox}. $\gamma_{analytical}$ is calculated from eq. (3), assuming that the sum of inversion layer and gate depletion thickness is 1 nm.

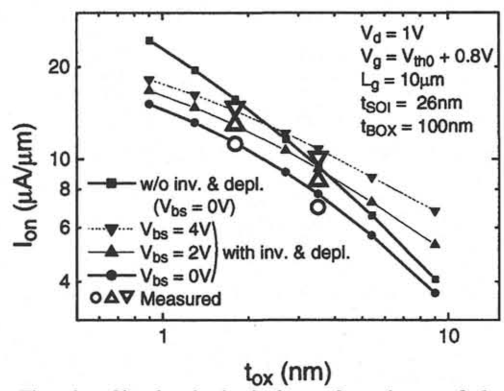

Fig. 6. Simulated physical t_{ox} dependence of I_{on}. Here, t_{SOI} and t_{BOX} are fixed, and it is assumed that $t_{ox\_ele} = t_{ox} + 1$ nm. Measured results are also shown.

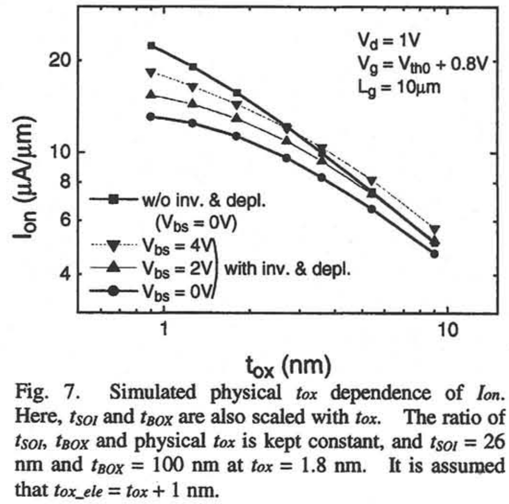

Fig. 7. Simulated physical t_{ox} dependence of I_{on}. Here, t_{SOI} and t_{BOX} are also scaled with t_{ox}. The ratio of t_{SOI}, t_{BOX} and physical t_{ox} is kept constant, and $t_{SOI} = 26$ nm and $t_{BOX} = 100$ nm at $t_{ox} = 1.8$ nm. It is assumed that $t_{ox\_ele} = t_{ox} + 1$ nm.

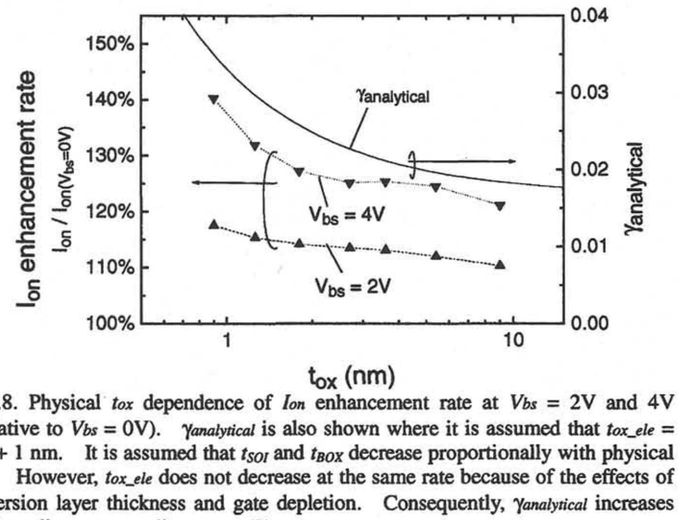

Fig.8. Physical t_{ox} dependence of I_{on} enhancement rate at V_{bs} = 2V and 4V (relative to V_{bs} = 0V). $\gamma_{analytical}$ is also shown where it is assumed that $t_{ox\_ele} = t_{ox} + 1$ nm. It is assumed that t_{SOI} and t_{BOX} decrease proportionally with physical t_{ox}. However, t_{ox_ele} does not decrease at the same rate because of the effects of inversion layer thickness and gate depletion. Consequently, $\gamma_{analytical}$ increases with scaling t_{ox} according to eq. (3).