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Optimum Conditions of Body Effect Factor and Substrate Bias in Variable Threshold Voltage MOSFETs

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1.Introduction

Variable threshold voltage MOSFET (VTMOS) has recently attracted much attention for ultra-low power VLSI applications at low supply voltage (V_{dd}) [1]. Utilizing the body effect, the substrate bias (V_{bs}) is controlled to shift the threshold voltage (V_{th}), and high V_{th} in the stand-by mode and low V_{th} in the active mode are attained. The V_{th} fluctuations are also suppressed by the V_{bs} control. The V_{th} shift (ΔV_{th}) is given by

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

where γ is body effect factor. Therefore, γ and V_{bs} are the most important device parameters in VTMOS and their optimization is essential to take full advantage of VTMOS. However, no report has been previously made on the optimum conditions of γ and V_{bs}.

In this study, the dependence of VTMOS performance on γ and V_{bs} is systematically investigated by simulation and the optimum conditions are discussed. It is found that V_{bs} should be as large as possible, while the optimum value of γ depends on the relationship between V_{bs} and V_{dd}.

2. Simulation and Results

Qualitative predictions: The off-current in the stand-by mode ($I_{off}(s)$) is set to 10^{-13} A/μm and the on-current in the active mode ($I_{on}(a)$) is compared in this study. The same results will be obtained when $I_{on}(a)$ is fixed and $I_{off}(a)$ is compared. Fig.1 shows schematic characteristics of VTMOS's with different γ. Device A has smaller γ than Device B. γ is defined as $\gamma \equiv |\Delta V_{th} / \Delta V_{bs}| = C_d/C_{ox}$, where C_d is depletion capacitance, and C_{ox} is gate oxide capacitance. On the other hand, subthreshold swing (S factor) is given by $S=60\,(1+C_d/C_{ox})$. Then the relation between γ and S is:

$$S = 60\,(1+\gamma). \quad [\mathrm{mV/dec}] \qquad (2)$$

This equation indicates that a device with larger γ has a larger S factor. When the off-current in the active mode ($I_{off}(a)$) is the same for the two devices, Device A with small γ will have higher $I_{on}(a)$ as shown in Fig.1. This is because Device A has steeper S swing (hence low V_{th}) and higher mobility due to weaker vertical electric field. However, Device A requires large $|V_{bs}|$ to attain large ΔV_{th} due to small γ.

Simulated device structures: Fig.2 shows schematics of device structures used in the simulation. Uniformly doped MOSFETs (Fig.2(a)) have low γ, while delta-doped MOSFETs have relatively high γ due to smaller depletion layer width [2]. Fig.3 shows the relation between $I_{off}(a)$ and $I_{on}(a)$ of the two devices. Device parameters used are based on the SIA roadmap in the 180nm generation [3]. Uniformly doped devices have higher $I_{on}(a)$ but the required $|V_{bs}|$ is extremely high due to very small γ. In order to investigate the effect of γ systematically in more wide ranges of $I_{on}(a)$ and $I_{off}(a)$, counter doped MOSFETs (Fig.2(c)) are also simulated, which have larger γ and smaller V_{th} (higher $I_{off}(a)$) than other two devices.

For constant $I_{off}(a)$: First, $I_{on}(a)$ of VTMOS is simulated at the condition of not only fixed $I_{off}(s)$ but constant $I_{off}(a)$, as shown in Fig.4. Fig.4 (a) shows the relation of γ and V_{bs} to attain the constant $I_{off}(a)$ of 2×10^{-8} A/μm and Fig.4 (b) shows the γ dependence of $I_{on}(a)$. At this condition, $|V_{bs}|$ should be as large as possible and a device with relatively small γ is preferable.

Optimum γ and V_{bs} in general: More general simulation results are shown in Figs.5 and 6. The only condition is the fixed $I_{off}(s)$ of 10^{-13} A/μm. Fig.5 shows contour lines of V_{bs} (solid lines) and γ (dashed lines) as a function of $I_{off}(a)$ and $I_{on}(a)$. When the device is fixed (i.e. γ is fixed), the relation between $I_{off}(a)$ and $I_{on}(a)$ is expressed in the corresponding contour line of γ. It is indicated by the contour lines of γ that $|V_{bs}|$ should be as large as possible to achieve higher $I_{on}(a)$, although $I_{off}(a)$ also increases. In actual devices, V_{bs} is limited by breakdown voltage or leakage current of the pn junctions.

Please note that all the contour lines of V_{bs} come to one point. This point corresponds to the device with $\gamma = 0$. It should be also noted that larger γ attains higher $I_{on}(a)$ above $|V_{bs}|$ of around 1.5V, while γ should be small to attain higher $I_{on}(a)$ below $|V_{bs}|$ of 1.2V. Fig.6 shows the same results in a different way, where contour lines of $I_{on}(a)$ are shown as a function of V_{bs} and γ. The slope of the contour lines changes from positive to negative at $|V_{bs}|$ of around 1.2V. This critical value of $|V_{bs}|$ roughly corresponds to V_{dd}.

Optimum condition of γ: The simulated results indicate that the optimum condition of γ in VTMOS depends on whether applied $|V_{bs}|$ is larger than V_{dd} or not. This interesting result is well explained qualitatively as follows. Let's consider dynamic threshold MOS (DTMOS) where gate is connected to body (i.e. $|V_{bs}| = V_{dd}$). DTMOS has an ideal S swing of 60 mV/dec and the value of $I_{on}(a)$ is almost similar to the device with $\gamma = 0$. When $|V_{bs}| > V_{dd}$, VTMOS has larger ΔV_{th} due to the body effect than DTMOS and shows higher $I_{on}(a)$ than the device with $\gamma = 0$. Therefore, larger γ will achieves larger body effect resulting in higher $I_{on}(a)$. On the other hand, when $|V_{bs}| < V_{dd}$, VTMOS has smaller ΔV_{th} than DTMOS and $I_{on}(a)$ are degraded compared with DTMOS. Since the degradation is smaller in VTMOS with smaller γ, VTMOS with small γ will achieves higher $I_{on}(a)$ than VTMOS with large γ. Actually, DTMOS has an additional effect due to ΔV_{th}, and the critical value of $|V_{bs}|$ is slightly smaller than V_{dd}.

3. Conclusions

The effects of γ and V_{bs} in VTMOS have been systematically examined by simulation at a condition of fixed stand-by off-current. When active off-current is limited, larger V_{bs} and smaller γ are preferable to attain higher drive current. When γ is fixed, $|V_{bs}|$ should be as large as the breakdown and leakage current permits. When V_{bs} is fixed by some reasons such as the breakdown, the optimum γ depends on whether $|V_{bs}|$ is larger than V_{dd} or not. These results will greatly help in designing ultra-low power VTMOS VLSIs.

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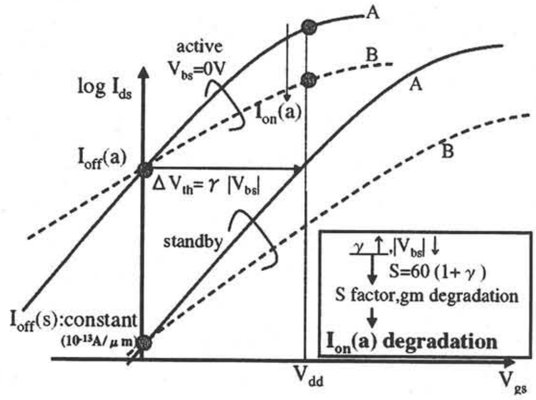

Fig.1. Schematic characteristics of VTMOS's with different γ. The off-current in the stand-by mode ($I_{off}(s)$) is set constant (10^{-13} A/ μ m) in this study. The off-current in the active mode ($I_{off}(a)$) is also set the same in this figure.

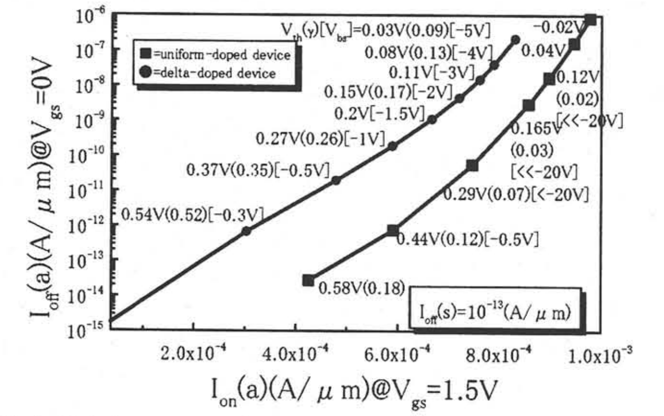

Fig.3. Relation between $I_{off}(a)$ and $I_{on}(a)$ of uniformly doped MOSFETs and delta-doped MOSFETs. V_{th} and γ of each device are shown. V_{bs} required to attain $I_{off}(s)$ of 10^{-13} A/ μ m is also shown.

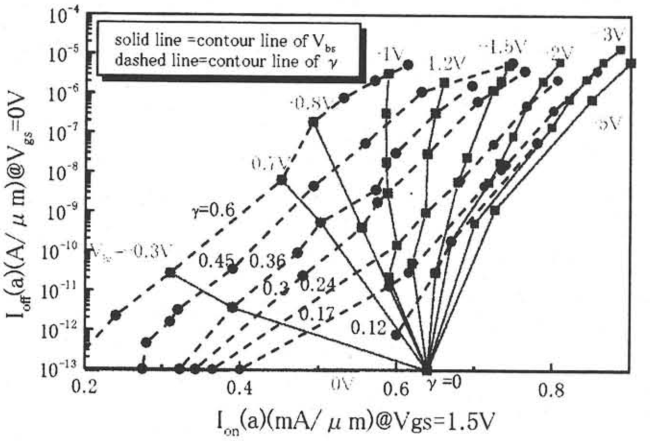

Fig.5. Contour lines of V_{bs} (solid lines) and γ (dashed lines) in VTMOS as a function of $I_{off}(a)$ and $I_{on}(a)$.

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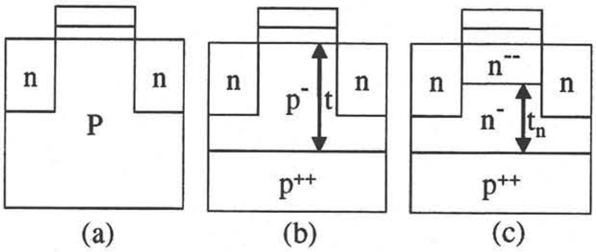

Fig.2. Schematic structures used in simulation. (a) Uniformly doped MOSFET, in which the channel concentration is varied to change γ and V_{th}. (b) Delta-doped MOSFET [2] in which the thickness of low concentration layer is varied to change γ and V_{th}. (c) Counter doped MOSFET, in which the thickness and concentration of n- layer is varied to change γ and V_{th}. (V_{dd}=1.5V, L_g=0.18 μ m, t_{ox}=3nm, X_j=50nm)

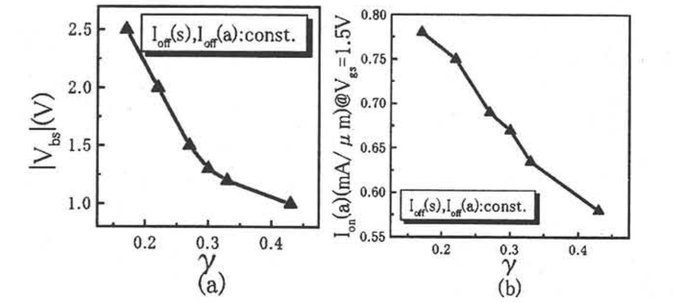

Fig.4. Simulation results at the condition of constant $I_{off}(a)$ of 2×10^{-8}A/ μ m. (a) Relation between γ and V_{bs} to attain $I_{off}(a)$ of 2×10^{-8}A/ μ m. (b) γ dependence of $I_{on}(a)$.

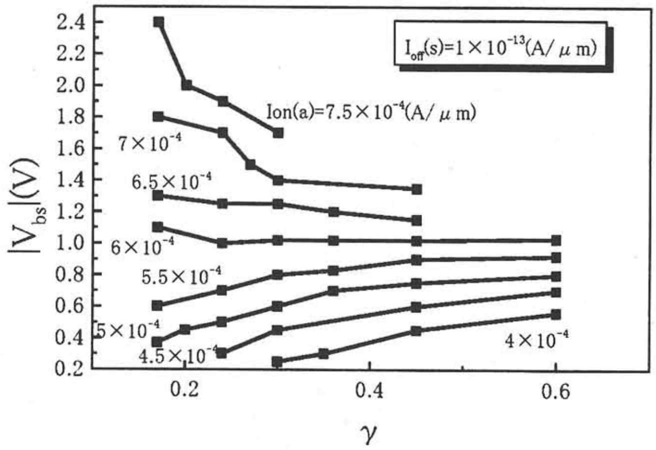

Fig.6. Contour lines of $I_{on}(a)$ in VTMOS as a function of V_{bs} and γ. V_{dd} is 1.5V. When V_{bs} is larger than 1.5V, higher $I_{on}(a)$ is attained by larger γ. On the other hand, when V_{bs} is less than 1.2V, higher $I_{on}(a)$ is attained by smaller γ.