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Quantitative Analysis of Hump Effects of Multi-Gate MOSFETs for Low-Power Electronics

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I. Introduction

Recently, for further improvement of performance, three-dimensional multi-gate MOSFETs have been investigated [1]. However, it was reported that multi-gate MOSFETs would suffer from a hump effect due to their non-planar channel structure which generates parasitic threshold voltages [2]. The hump effect increases off-current of MOSFETs because parasitic threshold voltages generally determine the sub-threshold characteristics of multi-gate MOSFETs as shown in Fig. 1. Thus, for low-power electronics, it is necessary to investigate the hump effect quantitatively.

In this paper, the accurate values of parasitic threshold voltages of multi-gate MOSFETs were extracted to evaluate the hump effect by using three-dimensional device simulation for the first time. Threshold voltages in each channel region were extracted by using the transconductance (g_m) change method [3]. Also, the dependence of parasitic threshold voltages on the doping concentration of a fin and the radius of curvature of fin corners was studied.

II. Parasitic Threshold Voltage Extraction

In order to confirm the validity of the transconductance change method for parasitic threshold voltage extraction, we assumed two parallel-connected single-gate planar MOSFETs, only whose gate workfunctions (Φ) and widths (W) are different from each other as shown in Fig. 2. Φ_n and W_n are defined as the gate workfunction and width of 'MOSFET n'. When (Φ_1, Φ_2) and (W_1, W_2) are (4.5, 4.9 eV) and (1, 10 μm), respectively, a hump is observed as shown in Fig. 3 (a). Fig. 3 (b) shows g_{m2} (=dg_m/dV_G) as a function of the gate voltage (V_G), which confirms that the transconductance change method successfully extracts threshold voltages of each MOSFET in that workfunction difference ($\Delta\Phi$) is the same as threshold voltage difference (ΔV_T) extracted by the transconductance change method. Threshold voltages of MOSFET 1 (V_{T1}) and 2 (V_{T2}) are 0.616 and 0.814 V, respectively. However, as Φ_2 decreases from 4.9 to 4.7 eV, with Φ_1 fixed at 4.5 eV, the transconductance change method fails to extract threshold voltages of MOSFET 1 and 2 because one of the g_{m2} peaks disappears due to small $\Delta\Phi$.

In order to evaluate the accuracy of the proposed method, we defined the relative error of extracted threshold voltages with regard to $\Delta\Phi$ as follows:

$$\textit{Relative error}\ (\%) = 100(\Delta\Phi - \Delta V_T)/\Delta\Phi.$$

Fig. 4 (a) shows the relative error with the variation of $\Delta\Phi$ and W_2/W_1. It turns out that as $\Delta\Phi$ and W_2/W_1 decrease, the relative error increases due to difficulty of g_{m2} peak sensing. However, as will be discussed in Section III, the transconductance change method is accurate enough to analyze hump effects of multi-gate MOSFETs. Also, it can extract threshold voltages of three parallel-connected MOSFETs as shown in Fig. 4 (b).

III. Analysis of Hump Effects of Multi-Gate MOSFETs

In this section, the transconductance change method is introduced to analyze the hump effect of multi-gate MOSFETs quantitatively. Three-dimensional device simulation has been carried out by using ATLAS simulator [4]. Multi-gate MOSFETs such as tri-gate and gate-all-around (GAA) MOSFETs are considered for simulation as shown in Fig. 5. The dimensions of tri-gate and GAA MOSFETs are the same except for the existence of a bottom gate in GAA MOSFETs. The thickness of gate oxide is 4 nm. The width and height of a fin are 42 nm. Doping concentration of a fin is 2×10^{19} cm^{-3}. The thickness of a buried oxide (BOX) layer is 50 nm. The workfunction of gate electrodes is 4.17 eV.

We extracted main threshold voltage ($V_{T,main}$) and parasitic threshold voltages ($V_{T,corner}$) of tri-gate and GAA MOSFETs by using the transconductance change method as illustrated in Fig. 6 (a). For the first time, it was observed that tri-gate MOSFETs have two different values of parasitic threshold voltages ($V_{T,corner1}$ and $V_{T,corner2}$) as illustrated in Fig. 6 (b). It results from the structural differences between upper and lower corners of a fin. Since the upper corners are controlled more strongly than the lower ones by the gate voltage, $V_{T,corner1}$ is lower than $V_{T,corner2}$. However, in the case of GAA MOSFETs, only one parasitic threshold voltage ($V_{T,corner}$) exists since there is no structural difference between upper and lower corners. To relieve the hump effect in three-dimensional MOSFETs, corner rounding and low fin doping concentration are used [6]. Fig. 7 (a) and (b) show the dependence of threshold voltages of tri-gate and GAA MOSFETs on fin doping concentration. As fin doping concentration decreases, each threshold voltage is observed to be converged into the same value-no hump. In the case of tri-gate MOSFETs, $V_{T,corner2}$ is converged to $V_{T,main}$ when the fin doping concentration is 5×10^{18} cm^{-3}. Also, the hump effect is completely removed when the fin doping concentration is below 1×10^{18} cm^{-3} both in the tri-gate and GAA MOSFETs. Fig. 8 (a) and (b) show threshold voltages as a function of the radius of curvature of fin corners. More than 16-nm radius of curvature is needed to suppress the hump effect when fin doping is 2×10^{19} cm^{-3} both in tri-gate and GAA MOSFETs.

IV. Summary

Transconductance change method is introduced to evaluate hump effects of multi-gate MOSFETs quantitatively for the first time. The effect of fin doping concentration and corner rounding on the hump effect is analyzed accurately. Since threshold voltages in each part of a multi-gate MOSFET can be extracted accurately, the proposed method will be very helpful low-power to multi-gate MOSFET design and compact modeling.

Acknowledgements

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Reference

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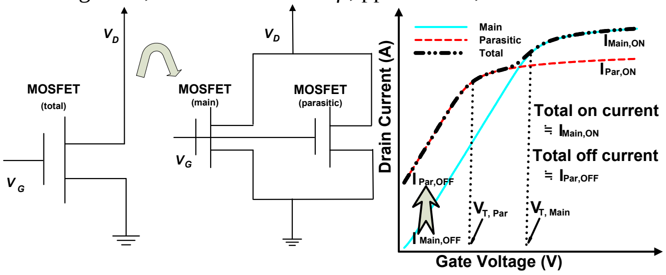

Fig. 1. Relationship between off-current and hump effects.

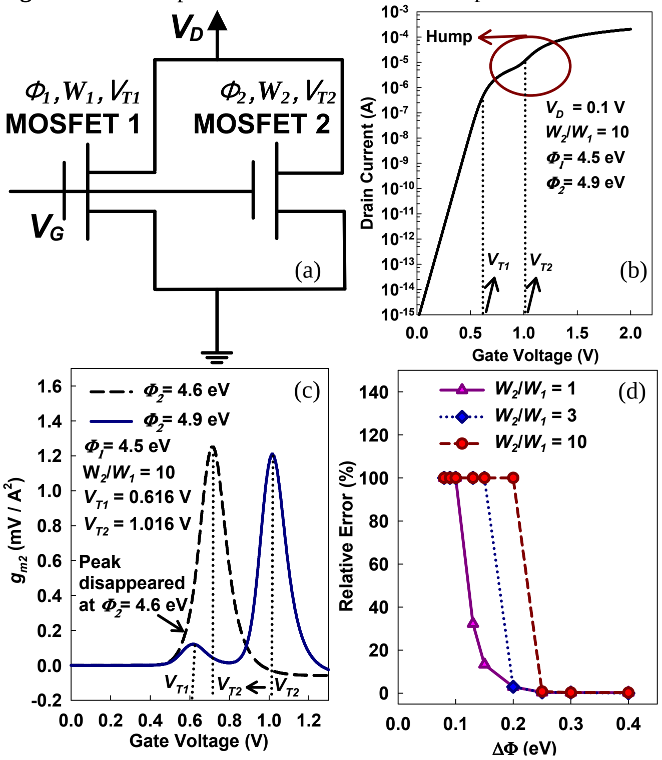

Fig. 2. (a) Parallel-connected single-gate MOSFETs. (b) I_D-V_G curve. (c) g_{m2}-V_G curves. (d) Relative error as a function of $\Delta\Phi$.

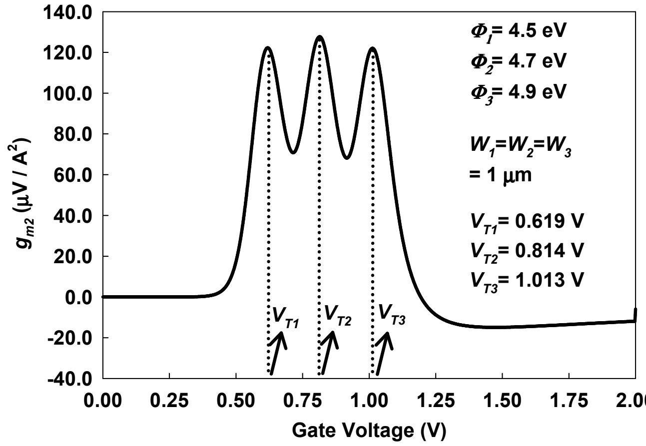

Fig. 3. g_{m2}-V_G curve for three parallel-connected single-gate MOSFETs.

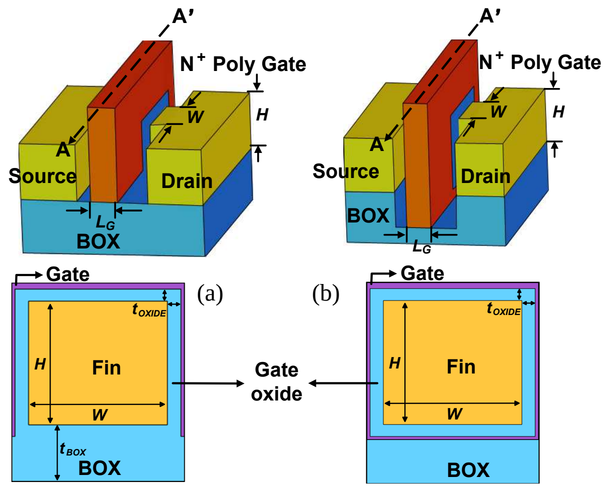

Fig. 4. Bird's eye and cross-sectional view (A-A') of (a) tri-gate MOSFETs and (b) GAA MOSFETs.

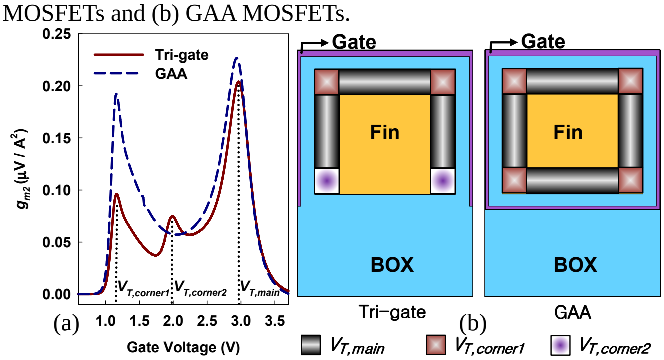

Fig. 5. (a) g_{m2}-V_G curves and (b) cross-sectional view tri-gate and GAA MOSFETs describing regions of extracted threshold voltages.

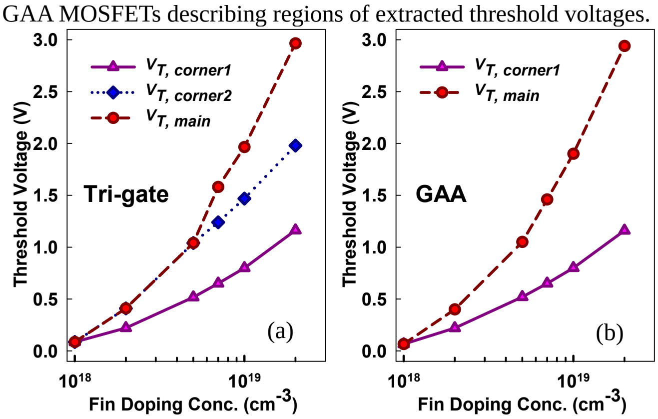

Fig. 6. Threshold voltages as a function of fin doping concentration of (a) tri-gate and (b) GAA MOSFETs.

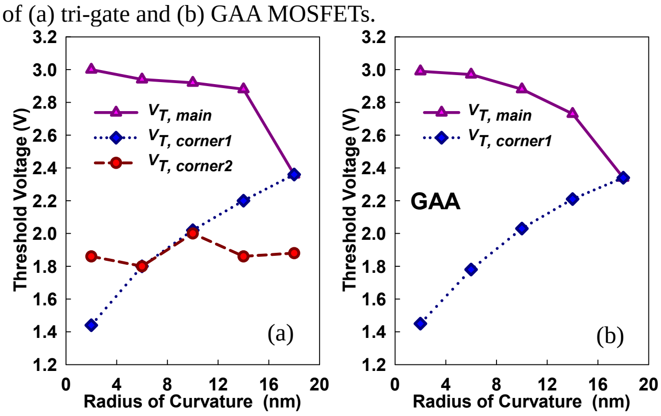

Fig. 7. Threshold voltages as a function of radius of curvature of (a) tri-gate and (b) GAA MOSFETs when fin doping is 2x10^{19} cm^{-3}.