Modeling of Short-Channel Effect for Ultra-Thin SOI MOSFET on Ultra-Thin BOX

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ABSTRACT

The threshold voltage dependency of the ultra-thin SOI MOSFETs is investigated. The focus is given on the back-gate voltage dependence as well as the short-channel effect. It is shown that extracted threshold voltage shows a linear depends of the back gate voltage, and an analytical equation is developed based on the Poisson equation considering all possible charges induced within the device. It is also shown that the short channel effect of threshold voltage depends on SOI layer thickness, and we modeled the effect successfully by considering the fully depleted condition. As the verification of the developed equations, we applied 2D-device simulation results.

Keywords: modeling of SOTB-MOSFET, threshold voltage, short channel effect

1 INTRODUCTION

MOSFETs are suffering from their short-channel effects. The SOI-MOSFET with the thin silicon layer has been developed to suppress the effect. The SOI-MOSFET technology has been further developed by reducing the SOI layer thickness called ETSOI-MOSFET. The ultimate structure of the ETSOI-MOSFET is the double-gate MOSFET with thin BOX layer. It has been demonstrated that the back-gate voltage can be effectively applied to control the threshold voltage realizing low voltage applications. The device is named SOTB-MOSFET (ultra-thin film SOI layer on ultra-thin BOX MOSFET)[1].

The threshold voltage is an important physical quantities for circuit designs, providing a measure for the short-channel effect. However, precise investigation is still missing for the V_{th} definition for the SOTB generation. Our purpose of this investigation is to derive an analytical equation of V_{th} for the device.

2 DEVICE FEATURE OF THIN SOI MOSFET

The main focus of this study is given on SOTB-MOSFET (ultra-thin film SOI layer on ultra-thin BOX MOSFET) developed for ultra-low voltage applications by controlling the threshold voltage (V_{th}). The thin SO layer can well control its threshold voltage by varying back-gate voltage (V_{bg}) from negative to positive due to the thin BOX layer thickness. Fig. 1 shows a schematic of the SOTB-MOSFET structure. The studied device parameters are depicted together. The back-gate voltage V_{bg} is utilized to control the V_{th} as demonstrated in Fig. 2. Charges induced within the device are not only located at the front gate but also at the back gate, depending on the bias conditions. With the complete surface-potential-based compact model HiSIM-SOTB, separation of the front-gate current and the back-gate current becomes possible. Finally we propose an analytical V_{th} model describing the threshold voltage shift considering both charges induced at the front gate as well as the back gate accurately. It is also demonstrated the influence of the technological variations on V_{th} is enhanced for the SOTB generation.

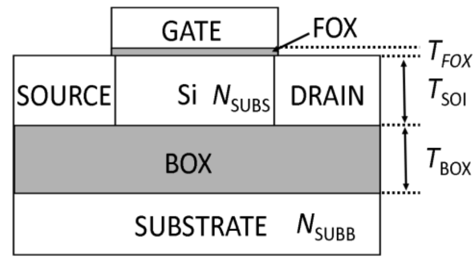

Fig. 1 Schematic of Silicon on Ultra-Thin BOX MOSFET developed for ultra-low power applications. T_{FOX}=2.5nm, T_{SOI}=10nm, T_{BOX}=10nm, L_{eff}=10nm, 1000nm, N_{SUBS}=3e17cm^{-3}, N_{SUBB}=4e16cm$^{-3.}$

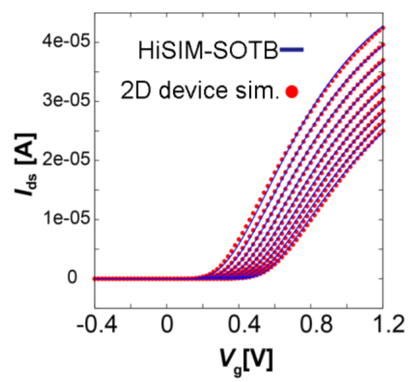

Fig. 2 Measured I_{ds}-V_{gs} characteristics. V_{bg}= -1 to 0.6V.

Surface potentials of HiSIM-SOTB and 2D-device simulation are compared in Fig. 3. In HiSIM model, accuracy of surface potential is very important because charges and currents are derived from the surface potentials. It is seen in Fig 3 shows that surface potentials of HiSIM-SOTB are in good agreement with those of 2D-device simulation. Difficulty in deriving the analytical V_{th} equation owes on the

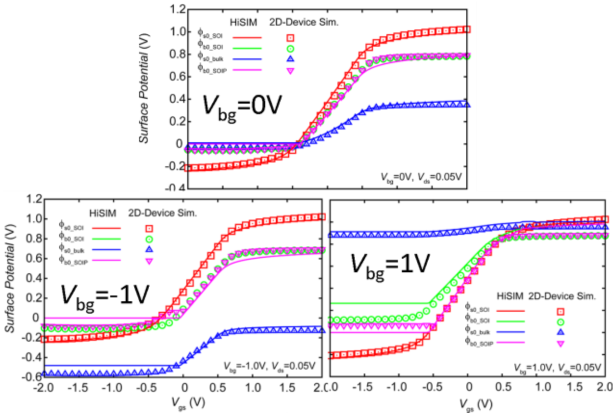

Fig. 3 Surface potential energy of SOTB-MOSFET.

fact that the surface potential $2\phi_B$, giving the threshold condition, is influenced not only by V_{gs} but also by V_{bg} as well as the device structure. Therefore the potential distribution from the device surface to the back-gate has to be considered for the derivation.

3 VTH DEFINITION OF BULK MOSFET

3.1 Extraction Method of V_{th}

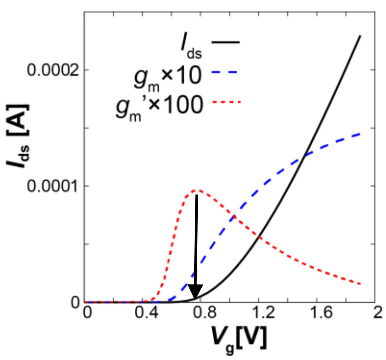

Fig. 4 V_{th} parameter extraction method.

In this paper, the V_{th} is chosen as a point where the g_{m} derivatives ($\frac{\Delta g_{\mathrm{m}}}{\Delta V_{\mathrm{gs}}}$) have their maximum value (see Fig.4). Features of this V_{th} determinatin method are: (i) the surface band-bending at the threshold is related to the classical threshold band-bending $2\phi_{\mathrm{B}}$. (ii) Determined V_{th} is not affected by device degradations (series resistance and surface roughness mobility degradation). [2]

3.2 V_{bg} Dependence of V_{th}

At the bulk MOSFET, threshold voltage is given as:

$$V_{\mathrm{th}} = V_{\mathrm{fb}} + 2\phi_{\mathrm{B}} + \frac{\sqrt{2\epsilon_{\mathrm{Si}} q N_{\mathrm{SUBS}}(2\phi_{\mathrm{B}} - V_{\mathrm{bg}})}}{C_{\mathrm{FOX}}} \tag{1}$$

where V_{fb} is a flat band voltage, $2\phi_{\mathrm{B}}$ is a surface potential of threshold condition, N_{SUBS} is inpurity concentration of the

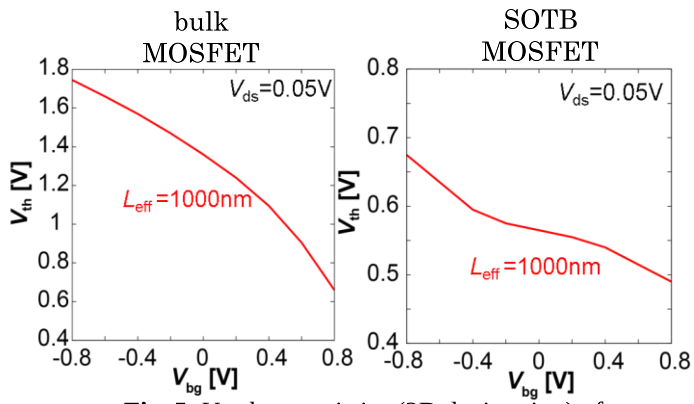

Fig. 5 V_{th} characteristics (2D device sim.) of bulk MOSFET (left), and SOTB MOSFET (right).

substrate, and C_{FOX} is a capacitance of FOX layer. Fig. 5 demonstrates SOTB MOSFET has the linear dependence of V_{bg} (Fig.5 right), which is completely different from the bulk MOSFET V_{th} characteristics (Fig.5 left). The threshold voltage definition of SOTB generation must be redefined.

4 MODELING OF THIN SOI/BOX MOSFET

4.1 Derivation of V_{th} Equation

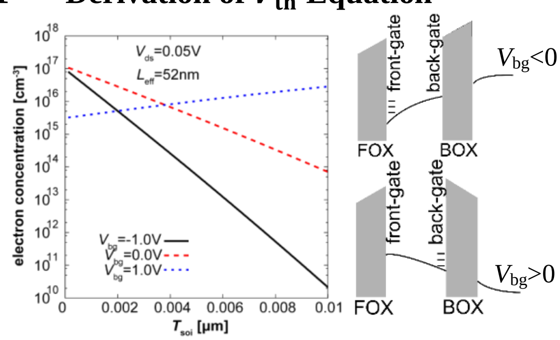

Fig. 6 Electron concentration of SOI layer where V_{ds} is fixed to 0.05V (2D-device sim.).

Fig. 6 demonstrates the electron distribution within the SOI layer for different V_{bg}, where the back-gate charge is induced when positive V_{bg} is applied. Therefore, in the case of SOTB generation, the equation of threshold voltage dependence on V_{bg} is different from that of bulk MOSFETs. Hence, we redefine the equation of the threshold voltage for SOTB generation. Basic equations used in HiSIM-SOTB are shown below:

$$\phi_{\mathrm{s}} = V_{\mathrm{gs}} - V_{\mathrm{fb}} - \Delta V_{\mathrm{th}} + \frac{Q_{\mathrm{i}} + Q_{\mathrm{b}} + Q_{\mathrm{dep}} + Q_{\mathrm{bulk}}}{C_{\mathrm{FOX}}} \tag{2}$$

$$\phi_{\mathrm{bulk}} = \phi_{\mathrm{b}} + \frac{Q_{\mathrm{bulk}}}{C_{\mathrm{BOX}}} \tag{3}$$

$$\phi_{\mathrm{b}} - \phi_{\mathrm{s}} = \frac{\frac{1}{2} Q_{\mathrm{dep,FD}} + Q_{\mathrm{bulk}}}{C_{\mathrm{SOI}}} \tag{4}$$

Equation of bulk charge is

$$Q_{\rm bulk} = \mp \,const0_{\rm bulk} \times \sqrt{\exp\{-\beta(\phi_{\rm bulk} - V_{\rm bg})\} + \beta(\phi_{\rm bulk} - V_{\rm bg}) - 1} \qquad (5)$$

where minus is for $V_{\rm bg} \leq 0$, and plus is for $V_{\rm bg} > 0$.

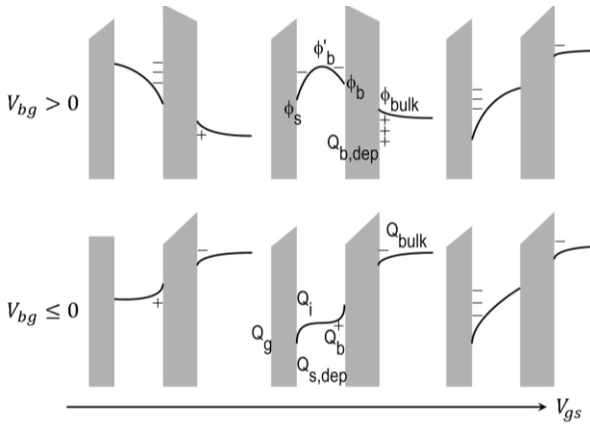

Fig. 7 Schematic of band energy of SOTB generation.

On the condition of $\beta(\phi_{\rm bulk} - V_{\rm bg}) \gg \exp\left(\beta\left(\phi_{\rm bulk} - V_{\rm bg}\right)\right) - 1$, equation (5) yields

$$Q_{\rm bulk} = \pm const0_{\rm bulk}\sqrt{\beta(\phi_{\rm bulk} - V_{\rm bg})} \qquad (6)$$

At the threshold voltage condition, basic equation (2) is written

$$V_{\rm th} = 2\Phi_{\rm B} + V_{\rm fb} - \frac{Q_{\rm FD}}{C_{\rm FOX}} + \frac{const0_{\rm bulk}\sqrt{\beta(\phi_{\rm bulk} - V_{\rm bg})}}{C_{\rm FOX}} \qquad (7)$$

Equations (3), (4) and (6) yields

$$\phi_{\rm bulk} = \frac{(2a+b) \pm \sqrt{(2a+b)^2 - 4(a^2 + bV_{bg})}}{2}. \qquad (8)$$

The charge induced at the bulk side is either positive or negative, dependent on the $V_{\rm bg}$ value. Namely the sign of $\phi_{\rm bulk}$ is either negative or positive. If the $\phi_{\rm bulk}$ sign is negative, $\phi_{\rm bulk} \simeq V_{bg}$ is obtained. Substituting (8) into (7), and applying the Taylor expansion method, resulting in the simplified equation

$$V_{\rm th} = 2\phi_{\rm B} + V_{\rm fb} - \frac{Q_{\rm FD}}{C_{\rm FOX}} + \frac{const0_{\rm bulk}}{C_{\rm FOX}}\sqrt{\frac{\beta\left(2a+b+\sqrt{(2a+b)^2-4a^2}\right)}{2}} + \frac{const0_{\rm bulk}}{C_{\rm FOX}} \frac{c\beta\left(-2+\frac{2b}{\sqrt{(2a+b)^2-4a^2}}\right)}{\sqrt{\beta\left(2a+b-\sqrt{(2a+b)^2-4a^2}\right)}} V_{\rm bg} \qquad (9)$$

where

$$a = 2\phi_{\rm B} + \frac{\frac{1}{2}Q_{\rm dep}}{C_{\rm SOI}}$$

$$b = 2\epsilon_{\rm Si} q N_{SUBS}\left(\frac{1}{C_{SOI}} + \frac{1}{C_{BOX}}\right)^2$$

$$c = 0.353553$$

Thus the final $V_{\rm th}$ equation for SOTB-MOSFET is recued to a linear function (equation. 9), and calculation results with the derived $V_{\rm th}$ equation is depicted in Fig. 8 as a function of $V_{\rm bg}$. For the studied case the SOI layer is so thin that it is fully depleted even under the threshold condition.

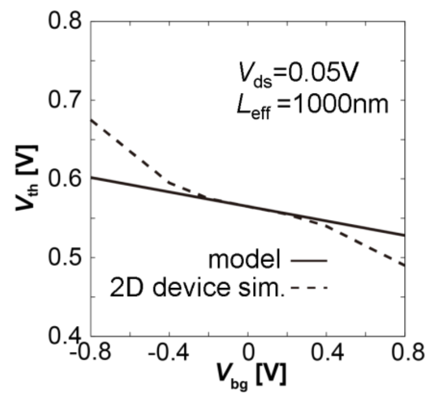

Fig. 8 Threshold voltage $\boldsymbol{V_{\rm th}}$ as a function of $\boldsymbol{V_{\rm bg}}$.

4.2 Modeling of Short Channel Effects

The short channel effect of $V_{\rm th}$ for bulk-MOSFETs is modeled by considering the lateral electric field $E_{\rm y}$ as equation (11).

$$V_{\rm th} = V_{\rm th0} - \Delta V_{\rm thSC} \qquad (10)$$

$$\frac{dE_{\rm y}}{dy} = \frac{2(V_{\rm bi} - 2\Phi_{\rm B})}{(L_{\rm gate} - PARL2)^2}\left(SC1 + SC2 \cdot V_{\rm ds} + SC3 \cdot \frac{2\Phi_{\rm B} - V_{\rm bg}}{L_{\rm gate}}\right) \qquad (11)$$

where $V_{\rm bi}$is a built-in potential, $PARL2$ is a depletion

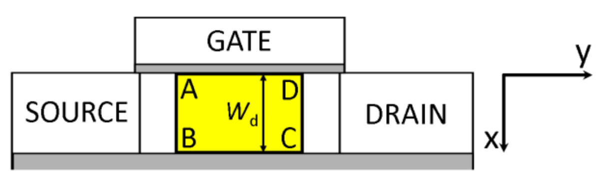

Fig. 9 Schematic illustration of the square ABCD in the SOTB-MOSFET channel region to which the Gauss' law is applied.

width of channel direction at the pn junction, and SC1-3 are model parameters. When the SOI layer is thick enough, the integration along B-C (see Fig. 9) is zero. However, the SOI layer thickness of SOTB is so thin that the depletion layer spreads to the surface of the BOX layer. Therefore the field at the surface of the BOX layer must be considered in the SOTB generation. Hence an equation below is derived

$$-\int_{A}^{B} E_{y1}(x)dx + \int_{C}^{D} E_{y2}(x)dx + \int_{D}^{A} E_{x1}(x)dy - \int_{B}^{C} E_{x2}(x)dy = -\frac{Q_s}{\epsilon_{S_i}} \quad (12)$$

where

$$-\int_{B}^{C} E_{x2}(x)dy = 0\ (W_d < T_{SOI})\ \text{ or} \neq 0\ (W_d > T_{SOI}).$$

Equation (12) gives

$$(E_{x1} - E_{x2})dy + W_d(E_{y2} - E_{y1}) = -\frac{Q_{dep}+Q_i}{\epsilon_{Si}}dy \quad (13)$$

With Gauss' law, $\epsilon_{Si}E_{Si} = \epsilon_{FOX}E_{FOX}$,

$$\left(E_{x1} - E_{x2} + W_d\frac{dE_y}{dy}\right)\epsilon_{Si} = (V_g - V_{fb} + \Delta V_{th} - \phi_s)\frac{\epsilon_{FOX}}{T_{FOX}}. \quad (14)$$

Then, we obtain

$$\Delta V_{th} = \frac{\epsilon_{Si}}{C_{FOX}}\left(-E_{x2} + W_d\frac{dE_y}{dy}\right). \quad (15)$$

This equation shows that E_{x2} suppress E_y effect. In other word, $E_x$suppresses the short channel effect. Now, we derive E_{x2} term. We consider the Poisson equation written

$$\frac{d^2\phi}{dx^2} = -\frac{\rho(x)}{\epsilon_{Si}} = -\frac{q}{\epsilon_{Si}}(p - n - N_A + N_D) = \frac{qN_{SUBS}}{\epsilon_{Si}} \quad (16)$$

where

$$W_{dMAX} = \sqrt{\frac{2\epsilon(2\phi_b)}{qN_{SUBS}}}.$$

At the threshold voltage condition of nMOS, $p = n = 0$, $N_D = 0$, and $N_A = N_{SUBS}$ $(0 < T_{SOI} < W_{dmax})$. Therefore,

$$E_{x2} = \frac{d\phi}{dx} = \int_{W_{dMAX}}^{x} \frac{qN_{SUBS}}{\epsilon_{Si}}dx = -\frac{qN_{SUBS}}{\epsilon_{Si}}(W_{dMAX} - T_{Si}). \quad (17)$$

Finally, resulting equation is

$$\Delta V_{th} = \frac{\epsilon_{Si}}{C_{FOX}}\left(-\frac{qN_{SUBS}}{\epsilon_{Si}}(W_{dMAX} - T_{SOI}) + W_d\frac{dE_y}{dy}\right). \quad (18)$$

We modeled the V_{th} equation for SOTB-MOSFET, and the model equation describes that gate-field on the BOX layer suppresses the short channel effect.

5 DISCUSSION

In the SOTB generation, there is no obvious ΔV_{th}dependency on the V_{bg} change in contrast to that of bulk MOSFET (Fig. 10).

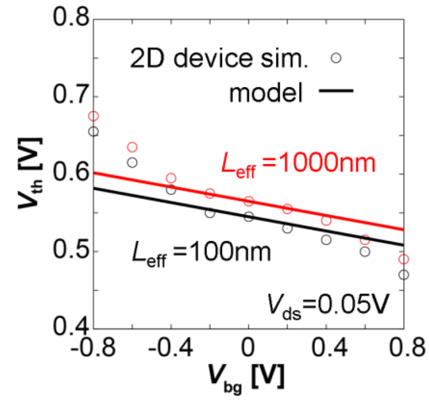

Fig. 10 V_{th} characteristics of SOTB MOSFET.

Fig. 11 shows we have modeled the dependency of short channel effect on SOI thickness successfully by considering the effect of thin SOI layer thickness, and the effect of the field on the surface of the BOX layer.

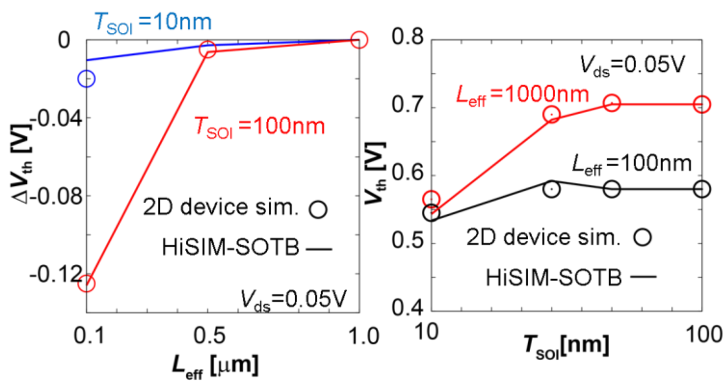

Fig. 11 Short channel effect of SOTB generation. Comparison of ΔV_{th}dependency on L_{eff} (left), and V_{th} dependency on T_{SOI} (right).

6 SUMMARY

In this paper, the dependency of V_{bg} on V_{th} and the effect of the SOI thickness on ΔV_{th} have been studied. Considering back gate charges and SOI layer thickness, we modeled the threshold voltage of V_{bg} dependency of the SOTB-MOSFET. Considering the field at the BOX layer, we also modeled the V_{th} short channel effect on T_{SOI}. From these results, we conclude that the threshold voltage of the thin SOI layer is successfully modeled.

REFERENCES

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[1] R. Tsuchiya et al., "Silicon on thin BOX: A new paradigm of the CMOSFET for low-power and high-performance application featuring wide-range back-bias control," in IEDM Tech. Dig., pp. 631–634, Dec. 2004.

[2] H. S.Wong et al., "Modeling of transconductance degradation and extraction of threshold voltage in thin oxide MOSFET's," *Solid State Electron.*, vol. 30, pp. 953–968, 1987.