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Investigation of Quantum-induced V_T Shift and Backgate-modulated V_T Properties for Ultra-Thin-Body InGaAs-OI/SOI Negative-Capacitance FETs

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Abstract

This work investigates the quantum-confinement (QC) induced threshold-voltage (V_T) shift and backgate-modulated V_T properties for ultra-thin-body (UTB) InGaAs-OI and SOI negative-capacitance FETs (NCFETs) using a theoretical quantum subthreshold model corroborated with TCAD numerical simulation. Our study indicates that, due to the action of negative capacitance, the NCFET possesses smaller QC-induced V_T-shift and smaller V_T sensitivity to the channel thickness than the underlying UTB MOSFET. In addition, the body-effect coefficient for the NCFET can become negative, and its magnitude exhibits distinct dependences on the front-gate oxide thickness and the BOX thickness from the MOSFET.

Introduction

Negative-capacitance FET (NCFET) is one of the most promising beyond-CMOS device candidates that may achieve a subthreshold swing (SS) smaller than the 2.3kT/q limit while maintain a high enough current drive (same current transport mechanism) as the MOSFET [1-3]. With high electron mobility, InGaAs is a very attractive channel material, and the ultra-thin-body (UTB) InGaAs-OI NCFET has been demonstrated recently [3]. For UTB InGaAs-OI or SOI transistors with undoped/lightly-doped channel, the threshold voltage (V_T) control and the multi-V_T capability with backgate modulation through the thin BOX are very crucial. With the scaling of channel thickness, the increase in V_T and V_T variation due to quantum confinement (QC) is becoming a concern. How might the action of negative capacitance impact these important V_T related properties for UTB NCFETs has rarely been known and merits investigation.

In this work, using a theoretical quantum subthreshold model corroborated with TCAD numerical simulation, we investigate the QC-induced V_T-shift and backgate-modulated V_T properties for UTB InGaAs-OI and SOI NCFETs.

Quantum Subthreshold Model for NCFET

Fig. 1 (a) shows a schematic sketch of the UTB NCFET structure (a ferroelectric layer on top of a UTB MOSFET) in this work. To accurately model the QC effect along the T_{ch} (i.e., x-) direction, the wave-function penetration into the front-gate oxide and buried oxide needs to be considered in analytically solving the Schrödinger equation under subthreshold [4-6]. In addition to structural confinement, the electrical confinement (which is V_{BS} dependent) is also taken into account by the correction of perturbation [5]. This model has been verified with TCAD numerical simulation. Fig. 2 shows that, under various V_{BS}, the ground-state eigen-energy E_0's calculated by our model are fairly accurate.

A quantum subthreshold model for the NCFET can be enabled by additionally considering the 1D steady-state Landau-Khalatnikov equation:

$$V_{FE} = T_{FE}\left(2\alpha Q_{G,mos} + 4\beta {Q_{G,mos}}^3 + 6\gamma {Q_{G,mos}}^5\right) \quad (1)$$

where T_{FE} is the ferroelectric thickness, α, β and γ are the ferroelectric parameters (see Table I) [7], V_{FE} is the voltage drop across the ferroelectric (i.e., $V_{G,nc}=V_{G,mos}+V_{FE}$), and $Q_{G,mos}$ is the stored charge density of the ferroelectric (which can be calculated through the gate charge of the underlying UTB MOSFET). It can be seen from Fig. 3 that our quantum subthreshold drain current models for both the NCFET and the underlying UTB MOSFET show satisfactory accuracy with TCAD numerical simulation. The SS is improved from ~69 to ~44 mV/decade (for InGaAs-OI) after the action of negative capacitance.

Results and Discussion

Using our model corroborated with TCAD numerical simulation, we investigate the QC-induced V_T-shift (ΔV_T) and body-effect related characteristics for InGaAs-OI and SOI NCFETs. Fig. 4 shows that, due to the QC effect, the ΔV_T increases substantially with the down-scaling of T_{ch}, and the ΔV_T of the NCFET is smaller than that of the underlying UTB MOSFET. The smaller V_T sensitivity to T_{ch} for the NCFET (Fig. 5) can be explained by the negative capacitance effect on the m-factor (see Eqn. (2) in Table I), which determines the QC-induced V_T-shift. Due to the negative capacitance effect (C_{FE} <0), the m-factor of the NCFET becomes smaller than that of the underlying UTB MOSFET.

Fig. 6 shows that the V_{BS} dependence of V_T for the NCFET exhibits an opposite trend to that of the underlying UTB MOSFET. In other words, the V_T of NCFETs increases with increasing V_{BS}. This behavior can be explained by Eqn. (3) (see Table I) and occurs when $|1/C_{FE}|$ is larger than $1/C_{tox}$ (see Fig. 1 (b) for the definition of the capacitance network).

Fig. 7 (a) and (b) compare the EOT dependence of the magnitude of the body-effect coefficient ($|dV_T/dV_{SB}|$) for the NCFET and the underlying UTB MOSFET. It can be seen that, opposite to MOSFET, the $|dV_T/dV_{SB}|$ of the NCFET increases with the down-scaling of EOT. This behavior can also be explained by Eqn. (3). Note that the SS of the NCFET also improves with decreasing EOT as shown in Fig. 7 (c).

Fig. 8 (a) further compares the T_{BOX} dependence of the magnitude of the body-effect coefficient for the NCFET and the underlying UTB MOSFET. It can be seen that the $|dV_T/dV_{SB}|$ of the NCFET increases as T_{BOX} increases, which is also quite different from the MOSFET behavior. Fig. 8 (b) shows the T_{BOX} dependence of the SS for the NCFET.

Acknowledgement

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References

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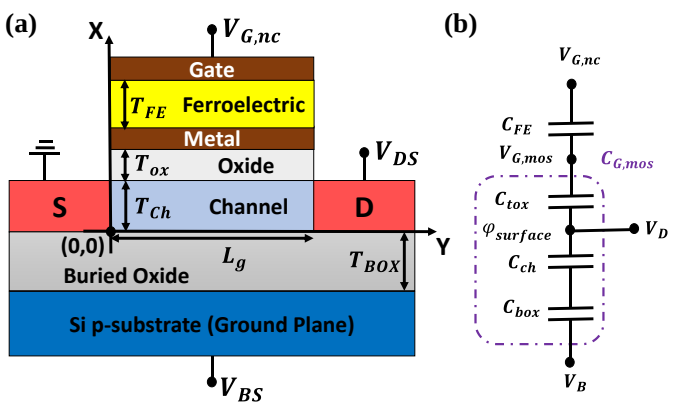

Figure 1. (a) Schematic sketch of a UTB NCFET structure. L_g is channel length. T_{Ch}, T_{FE}, T_{ox}, and T_{BOX} are thickness of channel, ferroelectric layer, front-gate oxide and BOX, respectively. (b) Equivalent capacitance model of the UTB NCFET.

Table I. Pertinent parameters and equations used in this work.

L_g	100 nm
T_{ch}	4 nm
T_{FE}	50 nm

Ferroelectric (HfZrO) [7]	
α	-7E8 m/F
β	1E12 m^5/F/C^2
γ	0 m^9/F/C^4

QC-induced V_T-shift $\Delta V_T \cong E_0 \times$ m-factor (2-a)

$$\text{m-factor}_{\text{MOSFET}} = 1 + \frac{C_{ch}C_{box}}{C_{tox}(C_{ch}+C_{box})} \quad \text{(2-b)}$$

$$\text{m-factor}_{\text{NCFET}} = \text{m-factor}_{\text{MOSFET}} \times \frac{C_{FE}+C_{G,mos}}{C_{FE}} \quad \text{(2-c)}$$

$$\frac{\Delta V_T}{\Delta V_{SB}} = C_{box}\left(\frac{1}{C_{tox}} + \frac{1}{C_{FE}}\right)\frac{C_{ch}}{(C_{box}+C_{ch})} \quad \text{(3)}$$

$$\frac{1}{C_{FE}} = T_{FE}\left(2\alpha + 12\beta Q_{G,mos}{}^2\right) \quad \text{(4)}$$

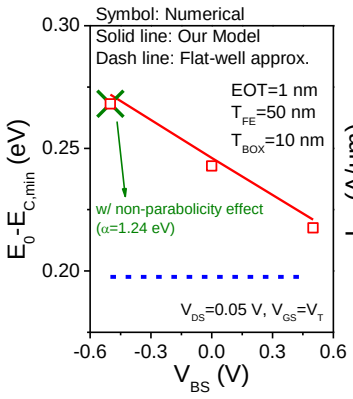

Figure 2. Impact of V_{BS} on the ground-state eigen-energy.

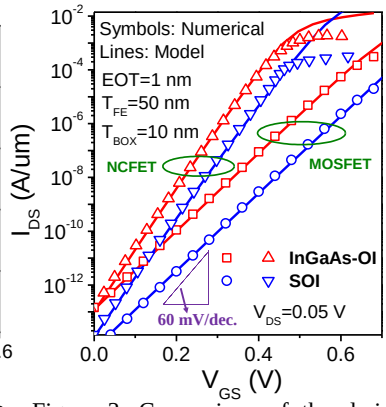

Figure 3. Comparison of the drain current from numerical simulation and our model.

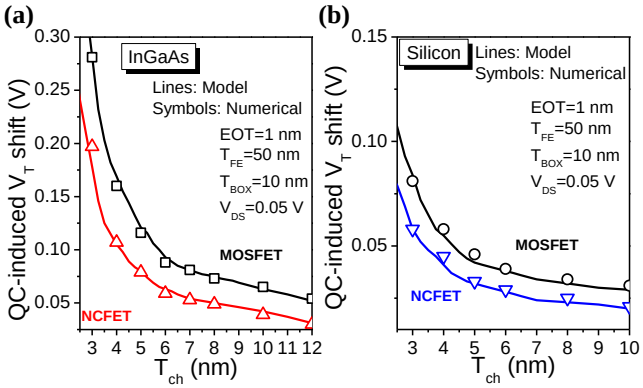

Figure 4. Impact of negative capacitance on the QC-induced V_T-shift for (a) InGaAs-OI and (b) SOI devices.

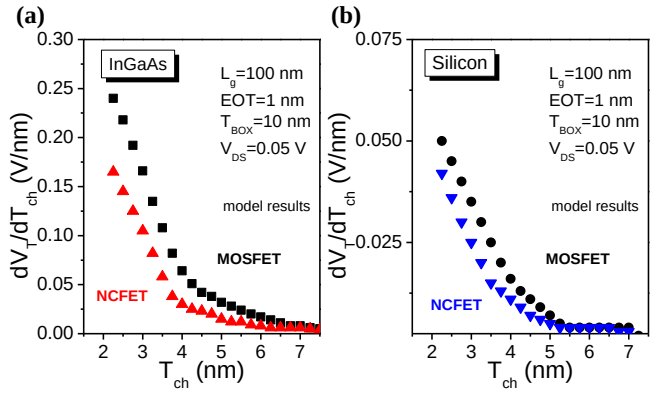

Figure 5. Impact of negative capacitance on the V_T sensitivity to T_{ch} for (a) InGaAs-OI and (b) SOI devices.

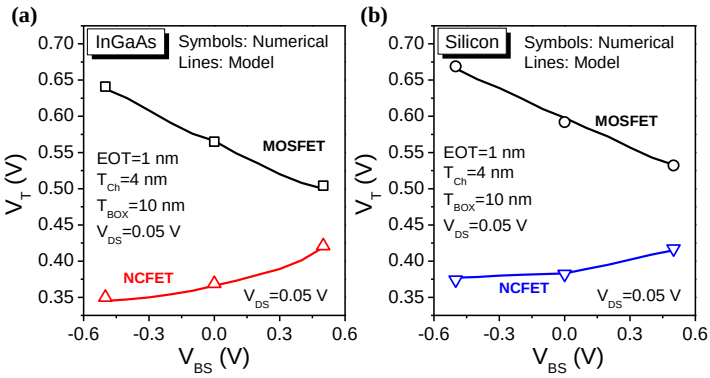

Figure 6. Impact of negative capacitance on the V_{BS} dependence of V_T for (a) InGaAs-OI and (b) SOI devices.

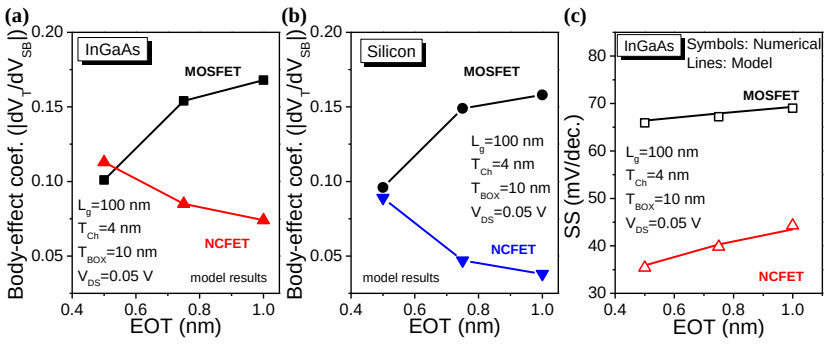

Figure 7. Impact of negative capacitance on the sensitivity of body-effect coefficient (|dV_T/dV_{SB}|) to EOT for (a) InGaAs-OI and (b) SOI devices. (c) Sensitivity of SS to EOT for InGaAs-OI devices.

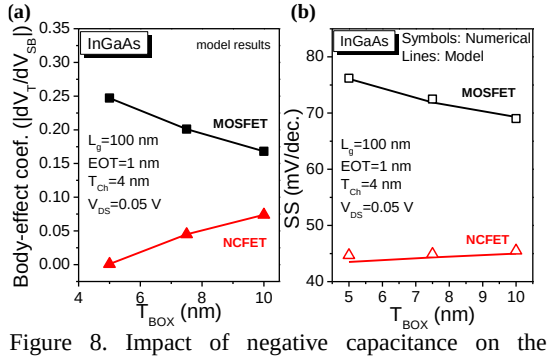

Figure 8. Impact of negative capacitance on the sensitivity of (a) body-effect coefficient (|dV_T/dV_{SB}|) and (b) SS to T_{BOX} for InGaAs-OI devices.