Impact of Quantum Confinement on Short-Channel Effects for Ultrathin-Body Germanium-on-Insulator MOSFETs

Yu-Sheng Wu, *Student Member, IEEE*, Hsin-Yuan Hsieh,
Vita Pi-Ho Hu, *Student Member, IEEE*, and Pin Su, *Member, IEEE*

***Abstract*—This letter investigates the impact of quantum confinement (QC) on the short-channel effect (SCE) of ultrathin-body (UTB) and thin-buried-oxide germanium-on-insulator (GeOI) MOSFETs using an analytical solution of Schrödinger equation verified with TCAD simulation. Our study indicates that, although the QC effect increases the threshold voltage (V_{th}) roll-off when the channel thickness (T_{ch}) is larger than a critical value $(T_{\mathrm{ch,crit}})$, it may decrease the V_{th} roll-off of GeOI MOSFETs when the T_{ch} is smaller than $T_{\mathrm{ch,crit}}$. Since Ge and Si channels exhibit different degrees of confinement and $T_{\mathrm{ch,crit}}$, the impact of QC must be considered when one-to-one comparisons between UTB GeOI and Si-on-insulator MOSFETs regarding the SCE are made.**

***Index Terms*—Germanium-on-insulator (GeOI), quantum confinement (QC), threshold voltage roll-off.**

I. INTRODUCTION

GERMANIUM as a channel material has been proposed to enable the mobility scaling for CMOS devices. As the higher permittivity makes Ge more susceptible to short-channel effects (SCEs), an ultrathin-body (UTB) germanium-on-insulator (GeOI) structure with thin buried oxide (BOX) has been suggested to improve the electrostatic integrity [1], [2]. With the scaling of channel thickness, the quantum-confinement (QC) effect may become significant and impact the SCE of scaled UTB devices. Using the density gradient model [3], Omura *et al.* [4] have observed increased threshold voltage (V_{th}) roll-off due to QC in UTB Si-on-insulator (SOI) devices. Whether there exists any difference between GeOI and SOI devices regarding the impact of QC on SCEs is not clearly known and merits investigation. In this letter, we tackle the problem using an analytically derived solution of Schrödinger equation verified with TCAD simulation. We report our new findings for UTB GeOI MOSFETs with thin BOX.

II. ANALYTICAL SOLUTION OF SCHRÖDINGER EQUATION

To consider the QC effect along the channel thickness (i.e., x-) direction, the Schrödinger equation can be express as

$$-\frac{\hbar^2}{2m_x}\cdot\frac{d^2\Psi_j(x)}{dx^2}+E_C(x)\cdot\Psi_j(x)=E_j\cdot\Psi_j(x) \qquad (1)$$

where E_j is the jth eigenenergy, $\Psi_j(x)$ is the corresponding wavefunction, and m_x is the carrier quantization effective mass. For long-channel undoped UTB MOSFETs, the conduction band edge $E_C(x)$ was usually treated as a triangular well [5]. However, to account for the source/drain coupling due to SCEs, the conduction band edge $E_C(x)$ in (1) should be treated as a parabolic well [6] with potential energy $E_C(x)=\alpha x^2+\beta x+\gamma$, where α, β, and γ are channel-length-dependent coefficients and can be obtained from the channel potential solution of Poisson's equation under the subthreshold region [7]. Using the parabolic-well approximation, the solution of (1) can be expressed as $\Psi_j(x)=\sum d_n\cdot x^n$ with the coefficients d_n's

$$\begin{aligned}
d_2 &= -\frac{m_x}{\hbar^2}(E_j-\gamma)\cdot d_0\\
d_3 &= -\frac{m_x}{3\hbar^2}\left[(E_j-\gamma)\cdot d_1-\beta\cdot d_0\right]\\
d_n &= -\frac{2m_x}{n(n-1)\hbar^2}\\
&\quad\times\left[(E_j-\gamma)\cdot d_{n-2}-\beta\cdot d_{n-3}-\alpha\cdot d_{n-4}\right],\ n\geq 4.
\end{aligned} \qquad (2)$$

The jth eigenenergy E_j can be determined by the boundary condition $\Psi_j(x=0)=\Psi_j(x=T_{\mathrm{ch}})=0$, where $x=0$ and $x=T_{\mathrm{ch}}$ (channel thickness) are defined as the interface positions of BOX/channel and channel/gate oxide, respectively. Thus, the eigenenergy and eigenfunction of short-channel UTB MOSFETs under the subthreshold region can be derived. We have verified our model using the TCAD simulation that numerically solves the self-consistent solution of 2-D Poisson and 1-D Schrödinger equations [8]. Fig. 1(a) and (b) shows that, for both the triangular potential well of long-channel devices and the parabolic well (due to SCEs) of short-channel ones, the E_j's calculated by our model are fairly accurate. It should be noted that a scalable QC model with accurate channel length dependence is crucial to this work.

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The authors are with the Department of Electronics Engineering and the Institute of Electronics, National Chiao Tung University, Hsinchu 30013, Taiwan (e-mail: pinsu@faculty.nctu.edu.tw).

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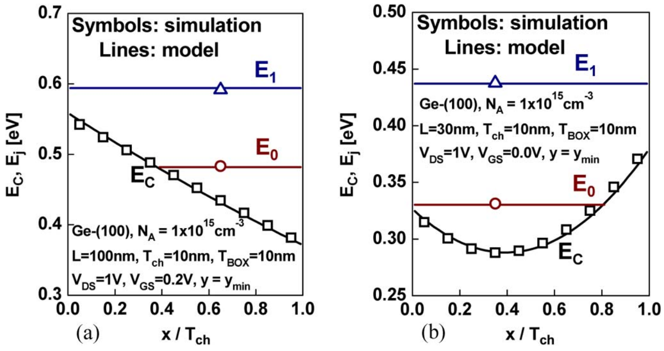

Fig. 1. Conduction band edge and quantized eigenenergies of lightly doped GeOI MOSFETs. (a) Long-channel device with triangular well. (b) Short-channel device with parabolic well.

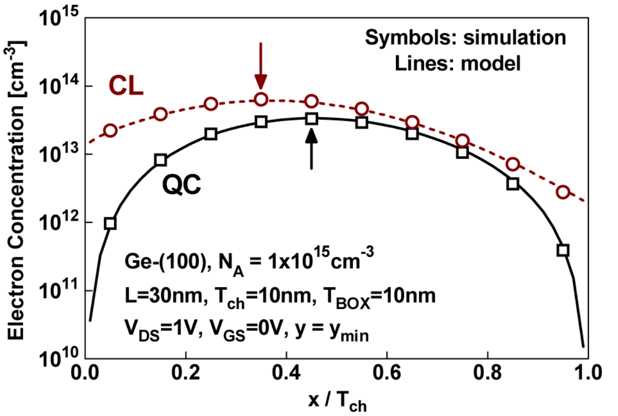

Fig. 2. Comparison of the electron density distributions with and without considering the QC effect. The electron density is calculated from 2-D density of states, eigenenergies, and wavefunctions.

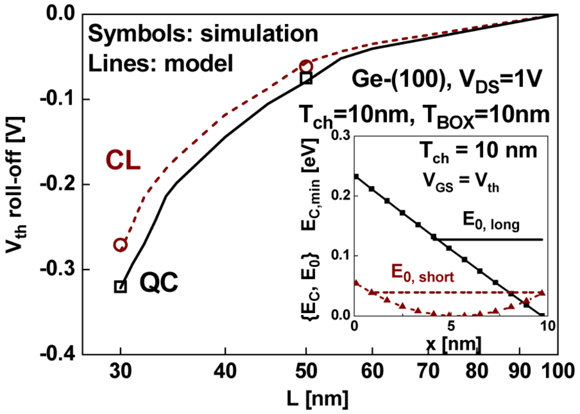

Fig. 3. Comparison of the V_{th} roll-offs between QC and CL models for $T_{\mathrm{ch}} = 10$ nm. The QC effect alters $L_{\min}$ (where the V_{th} roll-off $= -0.2$ V [12]) by about $+2$ nm. The inset indicates that, for GeOI MOSFETs with larger T_{ch}, the difference in E_0's of long-channel $(E_{0,\mathrm{long}})$ and short-channel $(E_{0,\mathrm{short}})$ devices is significant due to electrical confinement.

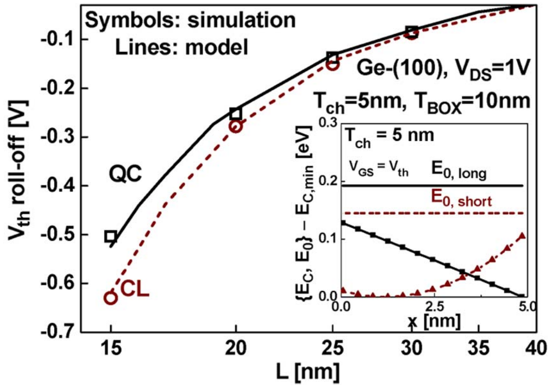

Fig. 4. Comparison of the V_{th} roll-offs between QC and CL models for $T_{\mathrm{ch}} = 5$ nm. The QC effect alters $L_{\min}$ by about -1 nm. The inset indicates that, for GeOI MOSFETs with smaller T_{ch}, the difference in E_0's of long-channel $(E_{0,\mathrm{long}})$ and short-channel $(E_{0,\mathrm{short}})$ devices is small because the degree of structural confinement is similar.

III. IMPACT OF QC ON V_{th} ROLL-OFF

To assess the impact of QC effect on V_{th}, the V_{th} is defined as the V_{GS} at which the average electron density of the cross section at $y = y_{\min}$ (the minimum potential along the carrier flow direction) exceeds a critical concentration that is equal to the channel doping. Note that the choice of other critical concentrations for determining V_{th} [9], [10] will result in a shift in V_{th} but will not affect the results of V_{th} comparisons in this study. Using the calculated eigenenergies and wavefunctions, the electron density can be derived [11]. Fig. 2 shows that the peak of electron density calculated by the classical (CL) model is not located at the channel/BOX interface $(x = 0)$ because the use of thin BOX (10 nm) instead of thick BOX suppresses the buried-insulator-induced-barrier lowering (BIIBL) [4]. Although the peak of electron density calculated by the QC model is shifted toward the channel center, the main current flow paths predicted by both models are quite similar for the UTB structure with thin BOX.

Fig. 3 shows that, for GeOI MOSFETs with channel thickness $(T_{\mathrm{ch}}) = 10$ nm, the V_{th} roll-off [defined as $V_{\mathrm{th}}(L) - V_{\mathrm{th}}(L = 100\ \mathrm{nm})$] predicted by the QC model is larger than that predicted by the CL model. This is consistent with the result reported for SOI MOSFET [4] and can be explained as follows. The V_{th} shift due to the QC effect can be expressed as $\Delta V_{\mathrm{th}}^{\mathrm{QM}} \cong S/(\ln 10 \cdot \mathrm{kT/q}) \cdot \Delta\psi_s^{\mathrm{QM}}$, with S being the subthreshold swing and $\Delta\psi_s^{\mathrm{QM}}$ being the equivalent surface potential shift due to the QC effect [5], [12]. The inset of Fig. 3 shows that, for GeOI devices with larger T_{ch} (10 nm), the "electrical confinement" [5] dominates the carrier quantization. The E_0 (ground-state energy) of the triangular well (for long-channel devices) is much larger than that of the parabolic well (for short-channel devices) because of the larger electric field in the triangular one. As $\Delta\psi_s^{\mathrm{QM}}$ is mainly determined by E_0, the $\Delta\psi_s^{\mathrm{QM}}$ and, thus, $\Delta V_{\mathrm{th}}^{\mathrm{QM}}$ for the long-channel device are larger than that of the short-channel one. Therefore, the V_{th} roll-off considering the QC effect is larger.

As the T_{ch} scales down, however, a different trend can be observed. Fig. 4 shows that, for GeOI MOSFETs with $T_{\mathrm{ch}} = 5$ nm, the V_{th} roll-off predicted by the QC model becomes smaller than that predicted by the CL model, which is opposite to the larger T_{ch} case and [4]. This cannot be explained by the reduction of BIIBL due to the QC effect [4], because in this study, thin BOX $(T_{\mathrm{BOX}} = 10\ \mathrm{nm})$ is used and the impact of BIIBL is not significant (see Fig. 2). Since the "structural confinement" [5] dominates the carrier quantization for GeOI devices with smaller T_{ch} (5 nm), the inset of Fig. 4 shows

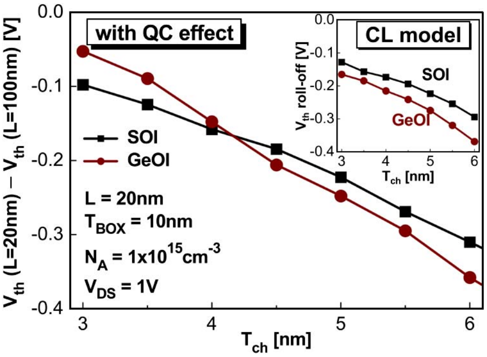

Fig. 5. $V_{\rm th}$ roll-off comparison between SOI and GeOI devices. As the QC effect is considered, a crossover near $T_{\rm ch} = 4$ nm can be seen.

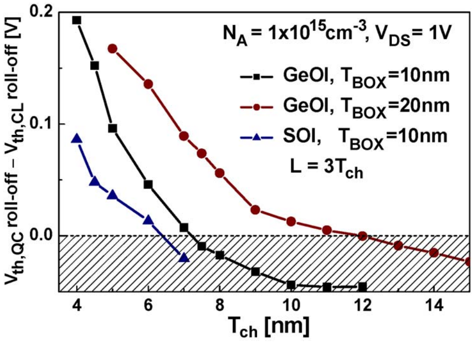

Fig. 6. Difference in $V_{\rm th}$ roll-offs between the QC and CL models depends on $T_{\rm BOX}$ and channel material. The filled region denotes that the QC effect enhances the $V_{\rm th}$ roll-off, while the blank region denotes that the QC effect suppresses the $V_{\rm th}$ roll-off.

that the E_0 (and, hence, $\Delta\psi_s^{\rm QM}$) of the long-channel device is close to that of the short-channel one. Nevertheless, due to the SCE, the subthreshold swing S of the short-channel device is larger than that of the long-channel one. Therefore, the $\Delta V_{\rm th}^{\rm QM}$ of the short-channel device is larger than that of the long-channel device, and the $V_{\rm th}$ roll-off considering the QC effect is smaller. This mechanism is important because it may alter the comparison result for $V_{\rm th}$ roll-off between SOI and GeOI devices. Fig. 5 shows that, contrary to the prediction by the CL model, the $V_{\rm th}$ roll-off for GeOI devices with smaller $T_{\rm ch}$ can be smaller than that of the SOI counterparts as the QC effect is considered.

In summary, depending on $T_{\rm ch}$, the QC effect may increase or decrease the SCE of UTB devices. The critical channel thickness $(T_{\rm ch,crit})$ determining whether the QC effect enhances or decreases the $V_{\rm th}$ roll-off depends on the BOX thickness $(T_{\rm BOX})$ and the channel material. Fig. 6 shows that the $T_{\rm ch,crit}$ of GeOI MOSFETs increases with $T_{\rm BOX}$. In addition, for a given $T_{\rm BOX}$, the $T_{\rm ch,crit}$ of SOI MOSFETs is smaller than that of the GeOI MOSFETs. This may explain why the suppression of $V_{\rm th}$ roll-off by the QC effect was not observed for the UTB SOI devices (with $T_{\rm ch} = 10$ nm) in [4].

IV. CONCLUSION

We have investigated the impact of QC on the SCE of UTB GeOI MOSFETs using a derived analytical solution of Schrödinger equation verified with TCAD simulation. Our study indicates that the impact of QC effect on the $V_{\rm th}$ roll-off of UTB GeOI MOSFETs shows two distinct trends. For GeOI devices with $T_{\rm ch}$ larger than $T_{\rm ch,crit}$, the QC effect increases the $V_{\rm th}$ roll-off, as previously observed in SOI devices [4]. However, for GeOI devices with $T_{\rm ch}$ smaller than $T_{\rm ch,crit}$, QC decreases the $V_{\rm th}$ roll-off. Since Ge and Si channels exhibit different degrees of confinement (because of the discrepancy in effective mass) and $T_{\rm ch,crit}$, the impact of QC must be considered when one-to-one comparisons [13], [14] between UTB GeOI and SOI MOSFETs regarding the SCE are made.

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