Ballistic Quantum-Mechanical Simulation of 10nm FinFET Using CBR Method

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Abstract. Simulating nanoscale devices with high accuracy, particularly towards 10nm feature sizes, requires highly efficient fully quantum mechanical simulators. In this work fully quantum mechanical simulator based on Contact Block Reduction (CBR) method has been used to investigate the behaviour of 10nm FinFET device in the ballistic regime of operation. Simulation results show the transformation from multiple channels into a single merged channel as the fin width is reduced gradually. Also we observe that short channel effects can be minimized by reducing the fin width which is evident from the device transfer characteristics presented in this paper.

1. Introduction

Scaling of conventional bulk-MOSFETs is approaching physical limits due to the upper bound imposed on the oxide thickness, S/D junction depth, etc. The double gate MOSFET has been proposed as a promising alternative structure [1] for future technology. With two gates controlling the entire fully depleted channel film, Short Channel Effects (SCE) can be greatly suppressed. FinFET is attractive to researchers due to its quasi planar structure, better immunity to SCEs, automatic self-alignment of gates with each other and with S/D [2]. Devices with gate length of 10 nm and oxide thickness of 1.7 nm have already been experimentally demonstrated [3].

Figure-1 depicts the geometry of FinFET being simulated. It consists of vertical channels formed in opposite faces of Si fin controlled by self-aligned double gate [4]. The fin is usually intrinsic or lightly doped to avoid channel dopant fluctuation and threshold voltage sensitivity to fin width. n⁺ polysilicon gate has been assumed as a gate electrode. In this work gate length of 10 nm and oxide thickness of 1.6 nm have been used. The fin width is varied over a range from 12 nm down to 8 nm.

2. Contact Block reduction(CBR) Method

Contact Block Reduction (CBR) method [6] allows one to calculate the ballistic transport properties of a two- or three-dimensional device that may have any shape, potential profile, and any number of leads. In this method, quantities such as the transmission function and the charge density of the open system can be obtained from the eigenstates of a corresponding closed system \( H^0 \psi_n = E_n \psi_n \) that needs to be calculated only once, and a solution of a very small linear algebraic system for every energy step.
Importantly, it is shown [9] that the calculation of relatively few eigenstates of the closed system is sufficient to obtain very accurate results. This makes it possible to apply the method to complicated three-dimensional structures with arbitrary number of leads.

According to the Landauer-Büttiker formalism, the current $J_{\lambda \lambda'}$ from lead $\lambda$ to lead $\lambda'$ can be expressed in terms of the transmission function $T_{\lambda \lambda'}(E)$ and the distribution functions $f_{\lambda}(E)$ of the leads

$$J_{\lambda \lambda'} = \frac{2e}{h} \int T_{\lambda \lambda'}(E) \left[ f_{\lambda}(E) - f_{\lambda'}(E) \right] dE$$

(1.1)

The transmission function can be obtained from the retarded Green’s function $G^R$ of the open device [9] and the coupling to the leads is introduced via the self-energy matrix $\Sigma$.

The retarded Green’s function $G^R$ can be calculated via the Dyson equation through a Hermitian Hamiltonian $H^0$ of a closed system represented by

$$G^R = A^{-1}G^0,$$

$$A = \left[I - G^0 \Sigma\right],$$

$$G^0 = \left[IE - H^0\right]^{-1}$$

(1.2)

In Ref. [6] it is shown that the inversion of the matrix $A$ can be easily performed using the property of the self-energy $\Sigma$ in real space representation: it is non-zero only at boundary regions which are in contact with external leads. We denote these regions with index $C$, and the rest of the device with index $D$. As a result the Green’s function matrix can be found in the form:

$$G^R = \begin{bmatrix} A^{-1}_{cc}G^0_{cc} & A^{-1}_{cd}G^0_{cd} \\ -A^{-1}_{dc}A^{-1}_{cc}G^0_{cc} + G^0_{dc} & A^{-1}_{dd}G^0_{dd} + G^0_{cd} \end{bmatrix}$$

(1.3)

The small left-upper matrix block $G^R_{cc} = A^{-1}_{cc}G^0_{cc}$ fully determines the transmission function Density of states, charge density etc. The fully self-consistent calculation has been accomplished using the predictor-corrector approach coupled to the CBR kernel. The particle density $n(\mathbf{r})$ can be easily obtained using the following expression,

$$n(\mathbf{r}) = \sum_{\alpha, \beta} \langle r | \alpha \rangle \langle \beta | r \rangle \xi_{\alpha\beta},$$

(1.4)

Where $\xi_{\alpha\beta}$ is the density matrix and is given by,
\[
\xi_{\alpha\beta} = \sum_{\lambda=1}^{\ell} \Xi^{(\lambda)}_{\alpha\beta}(E) f_\lambda(E) dE \tag{1.5}
\]
\[
\Xi^{(\lambda)}_{\alpha\beta}(E) = \frac{1}{2\pi} \left[ \text{Tr} \left( \begin{bmatrix} \beta \alpha \end{bmatrix} \Gamma_c^{-1} B_c^{-1} B_c^{(\lambda)} \Gamma_c \right) \right]_{\eta \rightarrow 0^+} \tag{1.6}
\]
\[
B_c = 1_c - \sum \Sigma_c G_c^u \tag{1.7}
\]

3. Simulation results

For wider fin width simulation result shows the presence of two distinct channels formed adjacent to each vertical gate. As fin width is reduced gradually inversion layers start to merge with each other towards the center of the fin. With 8 nm fin width only a single channel exists along the fin which participates in transport.

![Electron density across A-A' plane. Left panel: Fin width = 12 nm, Middle panel: Fin width = 10 nm, Right panel: Fin width = 8 nm. V_G = 0.2V, V_D = 0.1V.](image)

The transfer and the output characteristics of the three device structures we examined are shown in Figure 3. From the transfer characteristics results it is evident that smaller fin width gives better control of short channel effect which is depicted in Figure 4 (left panel). Clearly decreasing fin width improves subthreshold slope \cite{8}. In order to suppress short channel effects significantly it is suggested in \cite{9} that fin width \( \leq 0.7 \times \) gate length and gate oxide thickness \( \leq 0.3 \times \) fin width.

4. Conclusion

The CBR method provides very efficient way to solve the quantum transport problem in an open system; the CBR computational cost is mainly determined by the partial solution of the Hermitian eigenvalue problem of a closed system. Using CBR fully quantum-mechanical simulation has been done for 10nm FinFET device in the ballistic regime. Device characteristics of FinFET device significantly depend on fin thickness. Simulation results obtained in this work give insight for device optimization.
Figure 3. Left panel: Transfer characteristics, $V_D = 0.1V$ for different fin width. Right panel: Output characteristics for fin width = 12 nm

Figure 4. Left panel: Subthreshold slope vs. fin width, $V_D = 0.1V$, Right panel: Gate leakage

References
[1] C.H. Wann, K. Noda et al., IEEE Trans. Electron Dev., 43, 1742, (1996).
[2] H.S. Wong, K. Chan, and Y. Taur, IEDM Tech.Dig., 427, (1997).
[3] Bin Yu, Leland Chang, Shibly Ahmed et al., IEDM, pp 251-254(2002).
[4] D. Hisamoto, W-C. Lee, J. Kedzierski, et al., IEDM Tech. Dig., 1032, (1998).
[5] D. Hisamoto, W-C. Lee, J. Kedzierski, et al., IEEE Trans. Electron Dev., 47, 2320, (2000).
[6] D. Mamaluy, M. Sabathil, P. Vogl, J. Appl. Phys. 93, 4628 (2003).
[7] S. Datta, Superlattices and Microstructures 28, 253 (2000).
[8] Gen Pei et al., IEEE Trans. Electron Dev., 49, 1411, (2002).
[9] K. Suzuki et al. IEEE Trans. Electron Dev., 40, 2326, (1993).