3D NEGF Quantum Transport Simulator for Modeling Ballistic Transport in Nano FinFETs

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H R Khan, D Mamaluy and D Vasileska
Arizona State University
Tempe, AZ 85287-5706, USA

E-mail: hrkhan@asu.edu, mamaluy@asu.edu, vasileska@asu.edu

Abstract. Quantum effects play a dominant role in many of the state-of-the-art small size structures for which the applicability of the standard well-developed engineering tools based on a semi-classical transport description is very limited or even impossible. There are a number of methods developed by solid state theorists over the last several decades to address the issue of quantum transport. Among the most commonly used in nanostructure calculations schemes are the Wigner-function approach, the Pauli master equation, and the non-equilibrium Green's functions (NEGF). The growing popularity of the latest (sometimes referred to as the Keldysh or the Kadanoff–Baym) formalism is conditioned by its sound conceptual basis for the development of the new class of quantum transport simulators. We demonstrate in this work that the key to the successful application of the NEGF formalism to the 3D quantum transport problem in semiconductor nanostructures is the numerical efficiency of the contact block reduction (CBR) method. We also present some very important results from the 3D FinFET analysis, such as the importance of the third gate.

1. Introduction

Over the past three decades, silicon MOS-based integrated circuits, such as microprocessors, have consistently delivered greater functionality at higher performance and lower cost per function. An empirical observation called Moore’s Law [1] is commonly quoted to highlight the exponential rates of increase in circuit speed and integration density as MOS transistors have scaled down in channel length. As devices have gotten smaller, faster and cheaper, demand for higher device performance has increased because computer systems have grown more widespread and complex. The driving force for continued scaling is lowering the cost per function, as scaling leads to more functions per unit area of the chip.

Sometime within the next five years, traditional CMOS technology is expected to reach limits of scaling. As channel lengths shrink below 35 nm, complex channel profiles are required to achieve desired threshold voltages and to alleviate the short-channel effects. To fabricate devices beyond current scaling limits, IC companies are simultaneously pushing the planar, bulk silicon CMOS design while exploring

- alternative gate stack materials (high-k dielectrics and metal gates),
- band engineering methods (using strained Si or SiGe),

1 Dragica Vasileska, Arizona State University, Tempe, AZ 85287-5706, USA. E-mail: vasileska@asu.edu.
• alternative transistor structures (dual-gate structures, FinFETs, etc.), and
• alternative materials for reduced heat dissipation.

In fact, the challenge in identifying suitable high-k dielectrics and metal gates for both PMOS and NMOS transistors has led to early adoption of alternative transistor designs. These include fully-depleted (FD) SOI devices, dualgate (DG) structures, and FinFETs. Note that FD-SOI devices show promise for high-performance CMOS, microprocessors and system-on-a-chip designs. In such ultra-thin-body (UTB)-SOI structures, control of short-channel effects (SCE) and threshold voltage \(V_t\) adjustment can be realized with little or no channel doping. The purpose of this research work is to investigate alternative device designs, in particular the dual-gate and the FinFET device structure using the contact block reduction (CBR) method described in the next section for the solution of the non-equilibrium Green’s functions (NEGF) [2] problem.

2. Brief Description of the Approach Used

The CBR method [3,4] 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 like the transmission function and the charge density of the open system can be obtained from the eigenstates of a corresponding closed system \(H^0\) \(\psi_n\) \(E_n\) that need to be calculated only once, and the solution of a very small linear algebraic system for every energy step \(E\). The retarded Green’s function \(G^R(E)\) can be calculated via the Dyson equation through a Hermitian Hamiltonian \(H^R\) of a closed system represented by

\[
G^R(E) = A^{-1}(E)G^A(E), A(E) \equiv \left[ I - G^0(E)\Sigma(E) \right],
\]

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 written in the following form:

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

The small left-upper matrix block \(G^0_{cc}\) fully determines the transmission function, density of states, charge density, etc. The particle density \(n(r)\) can be obtained

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

where \(\xi_{\alpha\beta}\) is the density matrix and is given by,

\[
\xi_{\alpha\beta} = \sum_{\lambda=1}^{L} \int \Xi^{(\lambda)}_{\alpha\beta}(E) f_{\lambda}(E) dE.
\]

\[
\Xi^{(\lambda)}_{\alpha\beta}(E) = \frac{1}{2\pi} \text{Tr} \left[ \left( \bar{\varphi}^{(\lambda)} \bar{\varphi}^{(\lambda)} \right) \text{Tr} \left( \bar{B}_{\alpha}\Gamma^\dagger_{\beta} \bar{B}_{\beta} \right) \right]_{\eta=+},
\]

In Eq. (4), \(L\) denotes the total number of external leads of the device, index \(\lambda\) denotes individual lead number and \(f_{\lambda}(E)\) is the distribution function in lead \(\lambda\). The integration in Eq. (4) is performed over the energy interval, where both the density matrix distribution \(\Xi^{(\lambda)}_{\alpha\beta}(E)\) and the distribution function \(f_{\lambda}(E)\) are non-negligible. Consequently, the density matrix distribution defines the lower integration limit, and the distribution function – the upper integration limit.
Here we would like to note that the density matrix $\hat{n}_{\gamma}$ may also account for bound states, if they are present in the system. Indeed, the term $\Xi^{(\lambda)}_{\alpha\beta}(E)$ does not disappear when the coupling to the leads (represented by $\Sigma_c$ and $\Gamma_c$ terms) is zero (i.e. when system states are not bound to the outside world), but instead results in

$$\Xi_{\alpha\beta}(E)\delta(E-E_{\alpha})$$

that assures the inclusion of bound states into the total charge density. We point out, however, that in the case of numerical evaluation of Eq. (4), the delta-functions corresponding to the bound states should be integrated analytically, leading to the expression

$$\xi^{TOTAL}_{\alpha\beta} = \sum_{\gamma} \delta_{\alpha\gamma} \xi_{\gamma}(\varepsilon_{\gamma}) + \sum_{\lambda=1}^{M} \int \Xi^{(\lambda)}_{\alpha\beta}(E)f_{\lambda}(E)dE,$$

where the sum with index $\gamma$ is performed over all bound states (BS) in the system. While in the idealized ballistic case, it is generally unclear how to occupy these states if the bias is applied, in a presence of small scattering in the system, these quasi-bound states can be viewed as states that get occupied as a the result of scattering of carriers coming from one of the leads $\lambda = 1..L$. In the later case, if one knew ‘what lead has a carrier come from’ one could assign to the carrier the corresponding distribution function. Exploring this idea, one can make an assumption that the distribution function $f(\varepsilon_{\gamma})$ of the quasi-bound state $|\gamma\rangle$ depends on “the coupling strength” to the outside leads. If a quasi-bound state $|\gamma\rangle$ is coupled more strongly to lead $\lambda$, then it is reasonable to expect that its distribution function is close to the one of lead $\lambda$. Generally, one can speculate that if the scattering is small, then the quasi-bound states can be occupied according to the following approximate formula

$$\xi^{BS}_{\alpha\beta} = \sum_{\gamma\beta\lambda} \delta_{\alpha\gamma} \xi_{\gamma}(\varepsilon_{\gamma}) \left| \frac{\sum_{\lambda=1}^{M} F_{\gamma\lambda}(\varepsilon_{\gamma})}{\sum_{\lambda=1}^{M} F_{\lambda}} \right|^{2}$$

where the coupling strength, $F_{\gamma\lambda}$, of state $\gamma$ to lead $\lambda$ is

$$F_{\lambda} = \sum_{\gamma=1}^{M_{s}} \left| \chi_{\alpha\lambda}^{(\gamma)} \right|^{2}.$$

The summation in Eq. (8) is performed over (squares) of the absolute values of projections of states $|\gamma\rangle$ into $M_s$ transverse modes $\chi_{\alpha\lambda}^{(\gamma)}$ in lead $\lambda$. Here, it would be somewhat distracting to give a detailed motivation for this choice of the “coupling strength” $F_{\gamma\lambda}$, but we would like to note that the same quantity $F_{\lambda}$ can be used to determine what states $|\gamma\rangle$ should be treated as “quasi-bound” ones. We find this approach to be essential, in particular, for a superior convergence of the self-consistent cycle.

The self-consistent solution of the ballistic transport properties of an open device requires repeated solution of the Schrödinger and Poisson equations. In principle, it is possible to simply iterate the solution of the Schrödinger and Poisson equations and with enough damping this will yield a converged result. However, this approach leads to hundreds of iteration steps for each bias point that do not pose a reasonable scheme. To improve the convergence of a highly non-linear set of coupled equations, such as the Schrödinger-Poisson problem, the Newton algorithm is usually the first choice. But the exact Jacobian for the Schrödinger-Poisson set cannot be derived analytically, and its numerical evaluation is rather costly (while certainly possible, see e.g. Ref. [5]). In the case of a closed system this problem has been solved using the predictor-corrector approach [6]. The aim of this method is to find a good approximation for the quantum density as a function of the electrostatic potential where an expression for the Jacobian is known. At first, the Schrödinger equation is solved for the closed system with the Hartree potential, $\varphi_{H}(r)$, and the exchange and correlation, $\varphi_{XC}(r)$ taken into account. Then the local density of states $\rho(r,E)$ of the open system is calculated using the CBR method. The Hartree potential $\varphi_{H}$ and carrier density $n$ are then used to calculate the residuum, $F$, of the Poisson equation using,
where $A$ is the Poisson matrix. If the residuum is smaller than a predetermined threshold the solution is taken as converged one. If the residuum is still too large, the correction to the Hartree potential $\Delta \varphi_H (r)$ is calculated in the predictor step, where the predictor carrier density $n_{pr} (r)$ is calculated, assuming it to be the following functional of the change $\Delta \phi_H (r)$ in the Hartree potential:

$$
\begin{align*}
F[\varphi_H] = A \varphi_H - (n - N_D)
\end{align*}
$$

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$$
\begin{align*}
\begin{cases}
n_{pr} (r) = 2 \sum_{\lambda=1}^{L} \int \rho_{\lambda} (r, E) \left[ \frac{E + \Delta \varphi_H (r) - E_{\lambda}}{k_{\lambda}} \right] dE \\
A \left( \varphi_H (r) + \Delta \varphi_H (r) \right) = n_{pr} (r) - N_D
\end{cases}
\end{align*}
$$

where $f (x) = [1 + \exp (x)]^{-1}$ for a 3D system, the energy $E_{\lambda}^{(i)}$ is the Fermi level in lead $\lambda$, and factor 2 is taken into account for the spin degeneracy of the electrons. Note that the Jacobian for the system Eq. (10) can be easily found analytically:

$$
\begin{align*}
\frac{J_{pr}}{\varphi} = \frac{\partial F (r)}{\partial \Delta \varphi_H (r')} = A_{pr} + \frac{\partial n_{pr}}{\partial \Delta \varphi_H (r')} = \\
A_{pr} + \frac{2}{k_{\lambda} T} \sum_{\lambda=1}^{L} \int \rho_{\lambda} (f - 1) dE.
\end{align*}
$$

After applying the Newton method, the obtained correction to the Hartree potential $\Delta \varphi_H$ and the corresponding carrier density are used to update the Hartree $\varphi_H$, exchange $\mu_{X}^{LDA}$ and correlation $\mu_{C}^{LDA}$ potentials for the next step iteration $(i + 1)$ as follows:

$$
\begin{align*}
\varphi_{H}^{(i+1)} &= \varphi_{H}^{(i)} + \Delta \varphi_{H}, \\
\varphi_{XC}^{(i+1)} &= \mu_{X}^{LDA} [n_{pr}^{(i)}(\Delta \varphi_{H}^{(i)})] + \mu_{C}^{LDA} [n_{pr}^{(i)}(\Delta \varphi_{H}^{(i)})]
\end{align*}
$$

The loop is repeated until convergence is achieved, that is $|\Delta \varphi_H | < \varepsilon$, with $\varepsilon$ being the absolute error of the potential. We find that typically only very few (5-7) solutions of the Schrödinger equation are necessary to yield a converged solution with 3 correct digits in the potential and currents.

For the numerical implementation of a self-consistent scheme the choice of the energy grid is of high importance. To integrate the continuous part of the carrier density, the local DOS is discretized in energy space and then a simple numerical integration is done by summing up the values for each energy step weighted by the Fermi distribution and the energy grid spacing $\Delta E_k$ with $k$ being the index of the energy grid. Using a regular grid with constant grid spacing, the integral over the peak deriving from the resonant states is very poor since the relative distance between the nearest energy grid point $E_k$ and the resonant energy $E_n$ is, generally, arbitrary. Additionally, the resonant energy is slightly shifted with each iteration step, leading to a varying integration error during the self-consistent cycle, which acts as an obstacle against convergence for any self-consistent algorithm. Thus, a solution to this problem is to use the physical information about the system and employ an adaptive energy grid that resolves each known peak with a local energy grid of a few tens of grid points that is fixed to the resonant energy $E_n$. The location of resonant states is easy to find, since the resonant energies are close to (selected) eigenstates of the closed system. Another advantage of the CBR method is that these eigenstates are already known, since in this method the solution for the open system is being expressed in the basis of the closed system. As a result, the integration error is reduced compared to the case of using regular grid and remains constant within the iteration, since the grid is locally fixed to the shifting mode energies.

For highly doped devices it is important to include quantum-mechanical effects of exchange and correlation. In this work this is done via density functional theory and using local density approximation (LDA). Dynamic calculation of the required number of lead modes to optimize the computational time is also implemented in the simulator.
3. Problem Specification

In our previous research work that can be found in Refs. [7,8], simulation results obtained for DG FinFETs using the simulator that utilizes the 2-D contact block reduction method (CBR) to solve the non-equilibrium Green’s functions (NEGF) problem have been presented. In using the 2-D simulator described in Section 2 of this paper, the implicit assumptions taken into account are: (i) height (‘Y’ coordinate) of the FinFET is much larger compared to the width (‘Z’ coordinate) (Figure 1) so that it is reasonable to assume that carriers are not confined along Y direction and solution of the Schrödinger equation can be represented by simple plane waves and, (ii) the device can be viewed as a combination of parallel identical slices along the Y direction. However, the later assumption becomes invalid once the top gate in a FinFET and the buried oxide at the bottom of the device are taken into account. In addition, the first assumption is not always necessarily true for ultra-scaled devices as the Y directed length can be comparable to the Z directed length. For example, considering 10 nm FinFET and ‘area efficiency’ as the factor for the determination of fin height, the minimum height could be as low as 10 nm. In this case even the dimension of ultra thin fin (4 nm) is comparable to the fin height and the first assumption may lead to not very accurate picture of carrier transport.

One of the major goals of our research was to extend the 2-D CBR simulator to a fully self-consistent 3-D version so that device characteristics of ultra-small devices can be predicted with higher accuracy. However, the computational cost in 3-D simulator goes up significantly from that of 2-D simulator as it solves 3-D open-system Schrödinger and 3-D Poisson equations. Moreover, in 3-D domain, contact cross-sections are two dimensional instead of one dimensional for the 2-D case. One would then, within the CBR formalism, need to solve 2-D Schrödinger equation for the lead modes of all contacts and 3-D Schrödinger equation for device eigenstates for each equivalent valley.

Regarding 3-D simulation of DG and TG FinFETs, an ultra-scaled geometry has been considered to keep computational time within reasonable limits. The entire device domain is 30 nm×12 nm × YL where YL varies from 4 nm to 8 nm. Fin widths of 4 nm and gate oxide thickness of 1.2 nm have been assumed. Buried oxide is not simulated in this work. Source/drain doping of 2×10^19 cm^-3 is used with a doping gradient of 1.25 nm/decade over the source/drain-body junctions. Uniform doping of 2×10^19 cm^-3 has been assumed for the gate electrodes. For DG FinFETs fin height of 4 nm and 8 nm have been considered while for TG simulation only fin height of 4 nm is used. In addition, a simplified TG structure (as shown in Figure 2) has been used to save computational time.

![Figure 1](image_url)

Figure 1. (a) 3-D schematic view of a prototype FinFET, (b) top view along A-A’ cross-section and, (c) side view along B-B’ cross-section with the assumption that the top gate oxide is much thicker than the side gate oxide.
Figure 2. Left panel – side view of the FinFET geometry along line B-B' in Figure 1, Right panel – side view of simplified structure used for 3-D simulations in this work.

4. DG FinFET: 2-D vs. 3-D Simulation

At first the computational efficiency of both 2-D and 3-D simulator has been compared. The 2-D computational domain is 30 nm × 12 nm while the 3-D computational domain is 30 nm × 12 nm × 4 nm. Figure 3 shows the convergence in terms of Poisson residuum as the gate voltage varies from -0.3V to 0.4V at a fixed drain bias of 0.4V [9]. Each segment of the curves corresponds to a particular gate voltage and number of dots/square denotes the number of iterations needed to achieve convergence for that bias condition.

Figure 3. Residuum of non-linear Poisson equation for 2-D and 3-D case. The number of dots/square along each segment of the curves corresponds the number of iteration for that bias point. The value of applied voltage is shown close to each segment.

It is evident from Figure 3 that both 2-D and 3-D simulations converges well for each of the bias points with an average Poisson residuum smaller than $10^{-4}$ eV. Table 1 shows different parameters related to computational efficiency of 2-D and 3-D simulator for each iteration and valley.

Table 1. COMPUTATIONAL EFFICIENCY OF 2-D AND 3-D SIMULATOR FOR EACH BIAS POINT AND AVERAGED OVER VALLEYS

| Parameter                           | 2-D simulation | 3-D simulation |
|-------------------------------------|----------------|----------------|
| Grid points                         | 2356           | 25916          |
| Number of device eigenstates        | 90 (3.8%)      | 260 (1%)       |
| Avg. number of iterations per bias  | 5              | 9              |
| Eigen-solver time (per iteration)   | 15s            | 800s           |
| Open-system solver time(per iteration) | 36s           | 2200s          |
The impact of fin height on the device characteristics of DG FinFETs has been investigated using the 3-D simulator and the results have been compared with the corresponding 2-D simulations. For 3-D simulations, fin heights of 4 nm and 8 nm have been examined while the 2-D simulation is performed considering a slice in XZ plane. The corresponding transfer characteristics of the FinFET are shown in Figure 4 at a drain bias of 50 mV. It is important to mention that simulation results presented here are purely ballistic (i.e. no scattering has been included). Note that the values of the drain current are normalized by the height of the fin, \( h \) (per fin height value). For a fin height of 4 nm the drain current is significantly higher than the 2-D case at high gate voltages. As the fin height increases from 4 nm to 8 nm, the drain current decreases and approaches the values obtained with the 2-D simulation. This behavior can be explained as an effect of increasingly stronger quantum confinement as fin height is reduced. The electron density obtained from 2-D simulation along with average electron density (taken over the fin height of 4 nm), and electron density at the middle of the fin height for a fin height of 4 nm and 8 nm are shown in Figure 5. Two-dimensional simulation assumes no confinement effects along the height direction. As the fin height is reduced, confinement along height direction gradually becomes stronger and the density of electrons around the center (along the height direction) of the fin increases. As can be seen from the results presented in Figure 5, for a fin height of 4 nm the average (taken over fin height) electron density (Figure 4(b)) is smaller than the 2-D density but the electron density in a XZ plane at the middle of the fin height (Figure 4(c)) is significantly larger than the 2-D case due to the strong quantum confinement. Therefore, in this case the current is mainly determined by the confined electron around the center region of the fin even though the average density is smaller than the 2-D case. As the fin height is increased from 4 nm to 8 nm, the confinement along the height direction becomes relatively weaker and consequently the electron density at the middle of the fin height also reduces as shown in Figure 5(d). Therefore, the drain current also reduces and approaches the 2-D value.

![Figure 4](image_url)

**Figure 4.** Transfer characteristics of the considered FinFET with fin heights of 4 nm and 8 nm along with the 2-D simulation result at a drain bias of 50 mV.

The net gate leakage normalized by the fin height is shown in Figure 6 for both 2-D and 3-D simulations. Interestingly, these results clearly show that a 2-D gate leakage simulation can also serve as a very good approximation for double-gate devices: in this case the location of resonant peaks in gate currents is not affected by 3-D effects, only the magnitude of the peaks is affected due to the change of electron density in the channel, induced by the confinement in the height direction. Predictably, this property is no longer true for tri-gate devices, as it is demonstrated in the following section.
Figure 5. 2-D electron density, (a) 2-D simulation (Figure 1), (b) averaged over $h$ with $h = 4\text{nm}$, (c) at $y = h/2$ with $h = 4\text{ nm}$ and, (d) at $y = h/2$ with $h = 8\text{nm}$ The applied biases are $V_{GS} = 0.2\text{V}$ and $V_{DS} = 0.05\text{V}$.
Figure 6. Net gate leakage as a function of gate voltage for the considered FinFET with fin height of 4 nm and 8 nm along with the corresponding 2-D simulation result.

Figure 7. Output characteristics of the considered FinFET obtained from 3-D simulation with $h = 4$ nm along with the corresponding 2-D simulation at $V_{GS} = 0.1V$.

Finally, we compare the 2-D and 3-D output characteristics of DG FinFET. The results obtained from 3-D simulations for gate voltage of 0.1V are shown in Figure 7 along with the corresponding 2-D simulation. One can see that the output characteristics exhibit behavior similar to the transfer characteristics as fin height is reduced. The percentage increment in drain current (calculated as $(I_{3D} - I_{2D}) / I_{2D} \times 100$) is nearly constant for different drain voltages and is equal to 15%.
5. Double-Gate(DG) vs. Tri-Gate(TG) FinFET

In order to investigate the influence of the top gate on carrier transport, FinFET with active top gate has also been simulated. In this case the top gate oxide thickness is set to the same value as the side gate oxide thickness, 1.2 nm. Figure 8 shows the transfer characteristics of the DG and TG FinFETs at a drain bias of 0.4V.

![Figure 8. Transfer characteristics of double-gate and tri-gate FinFETs at a drain bias of 0.4V (linear and semi-log scale).](image)

From Figure 8 one can see significant improvement in device turn-on and turn-off characteristics which is mainly due to the additional control of the top gate over the channel. Figure 9 shows the net

![Figure 9. Net gate leakage vs. gate voltage for DG and TG FinFETs at $V_{DS} = 0.4V$.](image)
gate leakage as a function of gate voltage for a fixed drain bias of 0.4V. Adding the top gate significantly increases the off-state gate leakage as can be seen from Figure 9. The 3-D electron densities for DG and TG FinFETs for an applied gate voltage of 0.2V and drain bias of 0.4V are shown in Figure 10.

Figure 10. 3-D electron density for DG and TG FinFETs for $V_{GS} = 0.2$V and $V_{DS} = 0.4$V.

One can see from these simulation results that electrons are equally and strongly confined around the center of the fin from Y and Z directions since $t_s = h = 4$ nm. Also shown in Figure 11 are the electron densities in YZ plane at $X = 15$ nm for DG and TG FinFETs. Inclusion of the top gate increases the channel electron density significantly and consequently, yields higher drain current.
Figure 11. Electron densities in YZ plane at X = 15 nm at $V_{\text{GS}} = 0.2 \text{V}$ and $V_{\text{DS}} = 0.4 \text{V}$ for DG (top panel) and TG (bottom panel) FinFETs.

The output characteristics of DG and TG FinFETs for an applied gate voltage of 0.1V are shown in Figure 12. One can see the ‘flattening’ of the output characteristics for TG FinFET at smaller drain voltage compared to DG FinFET. Therefore, TG FinFET would provide less pronounced effects of channel length modulation by drain voltage.

Figure 12. Output characteristics of double-gate and and tri-gate FinFETs at a gate voltage of 0.1V.

Table 2 summarizes different performance matrices obtained from the simulations for DG and TG FinFETs. For the considered FinFET, adding a top gate increases the on-current increases by 35% and
decreases the subthreshold source-to-drain leakage by 85%. However, the total off-current \( (I_{SD,LEAK} + |I_G|) \) approximately doubles when top gate is added due to the significant increase in the off-state gate leakage as shown in Table 2. It is important to note that for all the simulations presented here, SiO₂ as the gate dielectric and thin gate oxide thickness of 1.2 nm are assumed. It is possible to reduce the amount of leakage by using high-K dielectric in the gate oxide. Overall, device characteristics can be improved by adding a top gate.

Table 2. PERFORMANCE MATRICES OBTAINED FROM THE SIMULATIONS OF DG AND TG FINFETS

| Parameter                          | DG     | TG     |
|------------------------------------|--------|--------|
| \( I_{ON} = I_{DS} @ V_{DS} = 0.4V, V_{GS} = 0.3V \) [\( \mu A \)] | 7.57   | 10.18  |
| \( I_{SD,LEAK} = I_{DS} @ V_{DS} = 0.4V, V_{GS} = -0.4V \) [nA] | 0.0319 | 0.0048 |
| Subthreshold swing [mV/dec]        | 73     | 70     |
| \( |I_G| @ V_{DS} = 0.4V, V_{GS} = -0.4V \) [nA] | 0.027  | 0.122  |

6. Conclusions

A new fully self-consistent 3-D quantum transport simulator based on CBR method has been developed during this research. Simulation results obtained using 3-D simulator for DG and TG FinFETs are presented. The limitations of 2-D simulator to capture the transport properties of ultra-small devices with strong confinement along two or more directions are explained with the 3-D simulation data for DG FinFET with progressively smaller height. The effects of top gate on carrier transport have been elucidated in terms of device on-current and particularly gate leakage. A comparative study has been made between DG and TG FinFET structure and overall, TG FinFET is found to be better performing device compared to DG FinFET.

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