The Impact of Body Doping Concentration on the Performance of Nano Dg-Mosfets: A Quantum Simulation

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This paper presents the effects of p-type body doping concentration on a symmetric double-gate MOSFET with 9 nm gate length, using full quantum simulation. The simulations are based on a self-consistent solution of the 2D Poisson equation and Schrödinger equation with open boundary conditions, within the non-equilibrium Green’s function formalism for a wide range of channel doping concentrations. The effects of varying the p-type body doping concentration parameter is investigated in terms of the drain current, potential energy profile, 2D electron density, on-off current ratio, subthreshold swing, drain induced barrier lowering, transconductance, drain conductance, voltage gain, and resistance. The simulation results show that a higher body doping improves the short channel effects.

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I. INTRODUCTION

It is well known that the advantages of silicon-on-insulator (SOI) MOSFETs over conventional transistors is related to reduced short channel effects (SCEs), increased circuit speed, and lower parasitic capacitances. To extend the scalability of the complementary MOS technology as well as to minimize the SCEs, some new kinds of SOI MOSFETs have emerged, such as double-gate (DG), triple-gate, and the gate-all-around MOSFET [1–5]. Of all the new kinds of MOSFETs, the DG MOSFETs represent the best candidate for controlling SCEs. In the DG MOSFET structure, the body doping effects are the crucial parameters that need to be considered.

Undoped DG MOSFETs can avoid the dopant fluctuation effect, which contributes to the variation of the threshold voltage and drive current [6–8]; moreover the undoped body in DG MOSFETs can enhance the carrier mobility, owing to the absence of depletion charges which can significantly contribute to the effective electric field, thus degrading the mobility [9]. Therefore, the DG MOSFET structure usually utilizes an undoped body. However, without body doping as a tool to adjust the threshold voltage, undoped DG MOSFETs need to rely on a gate work function to achieve multiple threshold voltages on a chip. Tunable metal gate technology then needs to be developed for DG MOSFETs. However, a

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metal gate with a tunable work function has not been integrated in DG MOSFETs, due to technological difficulties [10, 11]. Therefore, DG MOSFETs with a suitably doped channel are seriously investigated to set appropriate threshold voltages [12–14].

In this paper we consider ultra thin body DG MOSFETs with so small a gate length ($L_g = 9$ nm) and a high-k gate, that have emerged as possible candidates for device scaling at the end of the International Technology Roadmap for Semiconductors (ITRS) roadmap [15]. The simulation is based on the self-consistent solution of the 2-D Poisson equation and Schrödinger equation with open boundary conditions within the nonequilibrium Green’s function (NEGF) formalism, which is discussed in Section II. The effects of body doping on device performance, namely: drain current, on-off current ratio, electron density and potential profile along the channel, sub-threshold swing, drain induced barrier lowering (DIBL), transconductance, drain conductance, voltage gain, and resistance are investigated.

II. DEVICE STRUCTURE AND SIMULATION APPROACH

Fig. 1 shows the schematic of the symmetric DG MOSFETs and the corresponding coordinates, where the $x$-axis is along the channel (transport direction), the $z$-axis is along the quantum confinement direction, and the $y$-dimension is treated as being infinite. However, quantum confinement in the $z$-direction introduces subbands, and for an ultra thin body, only a few subbands are occupied. A high-k gate dielectric, highly doped source/drain contact, and short-channel length, have been considered. In this work, we use abrupt junctions and no S/D doping gradient, to provide a clear answer to the effects of the body doping.

![FIG. 1: An ultra-thin body DG MOSFET structure.](image-url)

Since the n-channel devices are analyzed, the p-type body with variable doping has to be assumed. The structural parameters of the devices are presented in Table I.

The 2D transport equation in the MOSFET channel region was solved by a mode space approach that splits the problem into two 1D problems [16]. Along the gate confinement direction (the $z$-direction in Fig. 1), the Schrödinger equation was solved for each
TABLE I: Parameters for the DG MOSFET structure used in simulation.

<table>
<thead>
<tr>
<th>Device parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of body: (t_{\text{body}}) [nm]</td>
<td>2</td>
</tr>
<tr>
<td>Equivalent oxide thickness: (E\text{OT}) [nm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Source/Drain length: (L_{SD}) [nm]</td>
<td>7.5</td>
</tr>
<tr>
<td>Gate length: (L_g) [nm]</td>
<td>9</td>
</tr>
<tr>
<td>Source/Drain doping concentration: (N_{SD}) [cm(^{-3})]</td>
<td>(2 \times 10^{20})</td>
</tr>
<tr>
<td>Power supply voltage: (V_{dd}) [V]</td>
<td>0.6</td>
</tr>
<tr>
<td>Gate work function: (\Phi) [eV]</td>
<td>4.20</td>
</tr>
<tr>
<td>Ambient temperature: (T) [K]</td>
<td>300</td>
</tr>
</tbody>
</table>

\[ x\text{-position independently, to generate the } i\text{th subband profile, } E_i(x), \text{ and the corresponding wave function, } \psi_i(x, z): \]

\[ -\frac{\hbar^2}{2m^*_z} \frac{d^2}{dz^2} \psi_i(x, z) - qV(x, z)\psi_i(x, z) = E_i(x)\psi_i(x, z), \tag{1} \]

where \(m^*_z\) is the effective mass along the \(z\)-direction, \(q\) is the electron charge, \(\hbar\) is Planck’s constant, and \(V(x, z)\) is the electrostatic potential.

In the longitudinal direction the nonequilibrium Green’s function (NEGF) approach was used to describe the ballistic and quantum transport phenomena. For the subband \(i\), with a plane wave eigenenergy, \(E_{k_j}\), we can write the retarded Green’s function relevant to the 1D transport as \([17–19]\)

\[ G(E) = \left[ EI - H[E_i(x), E_{k_j}] - \Sigma_S - \Sigma_D \right]^{-1} = \left[ E_i I - H[E_i(x)] - \Sigma_S - \Sigma_D \right]^{-1}, \tag{2} \]

where \(E_i\) is the longitudinal energy, \(E_i = E - E_{k_j}\), and \(\Sigma_S\) and \(\Sigma_D\) are the self-energies of the source and drain, respectively. These parameters indicate the effects on the finite device Hamiltonian due to the interactions of the device with the contacts. The spectral density functions due to the S/D contacts can be obtained as

\[ A_s = G \Gamma_s G^\dagger \text{ and } A_D = G \Gamma_D G^\dagger, \tag{3} \]

where \(\Gamma_s = i \left( \Sigma_s - \Sigma_s^\dagger \right)\) and \(\Gamma_D = i \left( \Sigma_D - \Sigma_D^\dagger \right)\). The source related spectral function is filled up according to the Fermi energy in the source contact, while the drain related spectral function is filled up according to the Fermi energy in the drain contact, and the diagonal entries of the spectral functions represent the local density-of-states at each node \([19]\). The 2D electron density matrix is obtained as

\[ n(E_i) = \frac{1}{\hbar a} \sqrt{\frac{m^*_z k_B T}{2\pi^3}} \left[ \Im_{-1/2} (\mu_S - E_i) A_s + \Im_{-1/2} (\mu_D - E_i) A_D \right], \tag{4} \]
where $m_y^*$ is the electron effective mass in the $y$-direction, $a$ is the finite difference lattice constant, $k_B$ is the Boltzmann constant, $T$ is temperature, $\Im_{-1/2}$ is the Fermi-Dirac integral [20, 21] of order $-1/2$, and $\mu_S(\mu_D)$ is the source/drain Fermi level. To obtain the total 2D electron density, we need to integrate Eq. (3) over $E_l$. We also need to sum the contributions from every conduction band valley and subband. Finally, we can get a 3D electron density by multiplying the corresponding distribution function $|\psi_i(x, z)|^2$ to the 2D electron density matrix at each longitudinal lattice node.

A 2D Poisson equation was then solved in the silicon channel and gate oxide to update the electrostatic potential (a nonlinear Poisson equation was solved to improve the outer loop convergence [22]). The iteration between the quantum transport equation and the Poisson equation was repeated until the self-consistency was achieved, and then the source-drain current was calculated as

$$I(E_l) = \frac{q}{\hbar^2} \sqrt{\frac{m_y^* k_B T}{2\pi^3}} \left[ \Im_{-1/2} (\mu_s - E_l) - \Im_{-1/2} (\mu_D - E_l) \right] T_{SD}(E_l).$$

The total current is obtained by integrating over $E_l$ and summing over all valleys and subbands. $T_{SD}$ is the transmission coefficient from the source contact to the drain contact in terms of the Green’s function, and is defined as

$$T(E) = \text{trace} \left( \Gamma_S(E)G(E)\Gamma_D(E)G^\dagger(E) \right).$$

### III. RESULTS AND DISCUSSION

Fig. 2 shows the Drain current (linear coordinates) for different body dopings as a function of the gate voltage. The output characteristics are identical and the changes are moderate from $N_b = 0$ cm$^{-3}$ to $N_b = 1 \times 10^{17}$ cm$^{-3}$ for body doping from $N_b = 0$ cm$^{-3}$ to $N_b = 1 \times 10^{18}$ cm$^{-3}$, while the corresponding changes are high from $N_b = 1 \times 10^{19}$ cm$^{-3}$ to $1 \times 10^{20}$ cm$^{-3}$. This shows that the major effect of the channel doping is to increase the threshold voltage as the doping level increases.

The threshold voltage is not sensitive to channel doping when the concentration is below $1 \times 10^{18}$ cm$^{-3}$. This is due to a high threshold voltage implying a higher voltage to switch it on; therefore a power consumption issue will prevail. Moreover, a substrate with specific (or added) body doping is sometimes needed when a threshold voltage adjustment is required.

The subthreshold characteristics (current on logarithmic scale) are shown in Fig. 3. The subthreshold region shows the tendency of steeper slope for higher body doping and the decreasing level in the lower concentration. However, as the doping level increased, the leakage current is decreased, and consequently the leakage current will also rise sharply.

Fig. 4 shows the potential energy profiles along the channel length for different body dopings. It is observed that there is a barrier region near the source end of the channel. This barrier determines the amount of electrons entering the channel. Its height is modulated by the body doping, with an increment of the body doping, the potential profile is increased.
FIG. 2: Drain current versus gate voltage for different body doping in linear scale at $V_{DS} = 0.6$ V.

FIG. 3: Drain current versus gate voltage for different body doping in logarithmic scale at $V_{DS} = 0.6$ V.
FIG. 4: Potential energy profile along the channel for different body doping at $V_{DS} = V_G = V_{DD} = 0.6$ V.

FIG. 5: 2D electron density along the channel for different body doping at $V_{DS} = V_G = V_{DD} = 0.6$ V.

and the amount of electrons entering the channel is decreased. Therefore the electron
density in the channel is decreased, as shown in Fig. 5.

With an increase of the body doping, the barrier height is increased, so the on current decreases. For a fixed gate voltage, the concentration of the body doping controls the height of the source to channel barrier; it is clear that with an increment of the body doping concentration at the p channel, the electron inversion is weak; therefore the on current is decreased. The reduction is salient from \( N_b = 1 \times e^{19} \, \text{cm}^{-3} \) to \( 1 \times e^{20} \, \text{cm}^{-3} \), as shown in Fig. 6(a).

![FIG. 6: (a) on current, (b) off current, and (c) on-off current ratio versus body doping concentration at \( V_{DS} = 0.6 \, \text{V} \).](1)

At the subthreshold region for a fully-depleted DG-MOSFET and quantum confinement, the mobile charge can be ignored and the body doping is a fixed charge. So by an increment of the body doping concentrations, the subthreshold current is decreased and therefore the off-current is decreased, as shown in Fig. 6(b). At a logarithmic scale for \( N_b = 1 \times e^{20} \, \text{cm}^{-3} \), the off current is reduced to \( 6.23 \times 10^{-6} \, (\mu \text{A}/\mu \text{m}) \), which is very small.

By increasing the body doping concentration, although both the on-current and off current are decreasing at higher body doping, but the rate of reduction in the off-current is faster than the on-current, in such a way the ratio of the on-current to off-current becomes very high at a body doping concentration from \( 10^{19} \) to \( 10^{20} \, \text{cm}^{-3} \), as shown in Fig. 6(c).
Fig. 7 shows the dependence of the subthreshold swing and drain induced barrier lowering (DIBL) on the silicon body doping concentration. The subthreshold swing stays almost constant when the doping level is less than \(10^{18}\) cm\(^{-3}\), while at a high doping level, it decreases slightly with an increase of the doping density. For \(N_b = 10^{20}\) cm\(^{-3}\), the subthreshold swing (64.6 mV/dec) is close to ideal (i.e., 60 mV/dec). When the doping level is less than \(10^{18}\) cm\(^{-3}\), the DIBL is fixed, but with an increment of the body doping to \(10^{20}\) cm\(^{-3}\), the DIBL decreases up to 45.4 mV/V, which means at high body doping concentrations the effects of the source/drain contact on the channel is diminished.

![Subthreshold swing and DIBL versus body doping concentrations](image)

**FIG. 7:** Subthreshold swing and DIBL versus body doping concentrations.

Fig. 8 (a), (b), and (c) show the transconductance (\(g_m\)), drain conductance (\(g_d\)), and voltage gain (\(g_m/g_d\)) versus body doping concentration at the on state, respectively. As can be seen from Fig. 8(a) and (b), \(g_m\) and \(g_d\) stayed constant at lower doping levels, then are decreased at higher doping due to the low 2D electron density at higher body doping. This means that the slope of the drain current profile versus gate voltage at a fixed drain voltage (\(V_{DS} = V_{DD} = 0.6\)) and the slope of the drain current versus drain voltage at a fixed gate voltage (\(V_G = V_{DD} = 0.6\)) are decreased at higher body doping. Also \(g_m\) has the best value at the lowest body doping and \(g_d\) and the voltage gain have their best value at the highest body doping.

Fig. 9 depicts the on resistance versus source/drain doping concentration at \(V_{SD} = V_G = V_{DD} = 0.6\) V. It is evident from Fig. 9, that, due to the reduction of the on current at higher body doping, the on resistance is increased with an increment of body doping, that is not suitable for a well design MOSFET. Also it means that the body doping increases the channel resistance.
FIG. 8: (a) transconductance, $g_m$, (b) drain conductance, $g_d$, and (c) voltage gain, $g_m/g_d$ versus body doping concentration at $V_{DS} = V_G = V_{DD} = 0.6$ V.

FIG. 9: On resistance versus body doping concentrations at $V_{DS} = V_G = V_{DD} = 0.6$ V.
IV. CONCLUSION

A self consistent solution of the NEGF and Poisson equations has been used in order to investigate the properties of p-type body doping concentration on the ultra thin double gate MOSFETs. For our nominal device, it is found that the output characteristics are very sensitive to the body doping from $1 \times 10^{19}$ cm$^{-3}$ to $1 \times 10^{20}$ cm$^{-3}$. At higher body doping concentrations, the short channel effects (SCEs) are improved, the transconductance, drain conductance, and on current are decreased, while the voltage gain, on-off current ratio, and on resistance are increased.

References