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# PERFORMANCE ANALYSIS OF QUANTUM TRANSPORT PHENOMENON IN FULLY DEPLETED DOUBLE GATE DECA NANOMETER SOI MOSFET

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**ABSTRACT**
Effects of carrier energy quantization in semiconductor surface region on performance of Fully Depleted Double Gate Deca Nanometer SOI MOSFET is theoretically considered. ATLAS device simulator is used to analyze operation and performance of our device. Simulation of device is based on drift diffusion transport model and energy balance transport model. Detailed comparison of both transport models shows accuracy and efficiency of energy balance transport model to predict electrical characteristics of ultrascaled devices due to incorporation of quantum effects in this model. Simulation results also show effect of carrier concentration on performance of our device for different concentrations.
**Keywords:** Drift-Diffusion (DD) Model, Energy Balance (EB) Model, Semiconductor Industry Association (SIA), Deca-Nanometer, Volume Inversion and ATLAS Simulator

## I. INTRODUCTION

Double Gate MOSFETs having thin Si film bodies will possibly constitute the main stream CMOS technology at the end of SIA roadmap [1]. The continuous scaling of MOS dimension requires the use of ultra thin gate dielectric layer and high substrate doping concentration which leads to high transverse electric field at oxide-semiconductor interface. Such a strong field at the interface gives rise to splitting of conduction band into discrete sub-bands and quantum mechanical effects become significant [2-3]. The carrier distribution and the transport properties of the carriers under the influence of quantum mechanical effect are quite different from the classical case. For example, in classical case, the motion of the carrier is not restricted in any direction but the quantum mechanical effect limits the carrier motion in direction parallel to the oxide-semiconductor interface only. The electrical characteristics predicted by the classical model could be very different from the one predicted using a quantum mechanical effect based model. In most quantum simulation being developed today, a recursive technique is used, either for the wave function [4] or, more frequently, for the green's function [5-7]. These approaches have been quite successful in describing steady state transport in a wide variety of 1-D, 2-D or 3-D semiconductor structures [8-11]. Recent studies show that in both quantum and classical transport frameworks, scattering mechanisms have significant role on the operation and performance of Double Gate Nanoscale MOSFETs [12-14]. In this paper, we carry out a simulation based study on transport mechanisms of Fully Depleted Double Gate Nanoscale SOI MOSFET. The commercially available ATLAS™ [15] device simulator has been used to obtain simulation results for our device. The ATLAS software solves

numerically the 2D Poisson's equation. Among the drift-diffusion (DD) model, energy balance (EB) model and hydrodynamic (HD) model available in ATLAS library, device simulation carried out in this paper is based on drift diffusion (DD) transport model and energy balance (EB) transport model.

Current density equations in drift-diffusion transport model are obtained by applying approximation and simplifications to Boltzmann Transport Equation. Drift-Diffusion (DD) transport model neglects quantization of electron energy. The drift-diffusion model is less accurate for nanoscale devices as it does not account for nonlocal transport effects. Influence of nonlocal transport effects such as velocity overshoot, diffusion associated with the carrier temperature and the dependence of impact ionization rates on carrier energy distributions is of prime importance for correct evaluation of electrical characteristics of ultra scaled Double Gate SOI MOSFETs. Applicability of energy balance transport model to nanoscale devices is essential because in contrast to conventional drift-diffusion transport model, it accounts for nonlocal transport effects. Energy balance transport model accounts for nonlocal transport effects by including additional equations for the carrier temperature in the current density expressions therefore energy balance transport model proves to be more accurate compared to drift-diffusion (DD) model.

## II. THEORETICAL MODEL DESCRIPTION

Due to importance of quantum mechanical effects in the MOS structure characterization, simplified investigation methods and modeling as well as thorough numerical investigations by self consistent solution of Schrödinger and Poisson's equations are developed. Since the self consistent solution of Schrödinger and Poisson's equations are very complex and expensive, some simplified methods of analysis are employed. Quantum mechanical corrections are usually derived either from the triangular well approximation (airy function approximation) or the variational technique .The most commonly used method is the triangular well approximation based on the assumption of a linear distribution of potential in the inversion layer i.e. the constant electric field in the inversion layer. This assumption allows to decouple Schrödinger and Poisson's equation. As a result, the analytical expression for the electron energy states is obtained

$$E_{ij} = \left(\frac{h^2}{2m_{xj}}\right)^{1/3}\left[\frac{3}{2}\pi q F_s (i - \frac{1}{4})\right]^{2/3} \qquad (1)$$

$$i = 1,2,3,....$$

where $F_s$ denotes the effective electric field in the semiconductor surface region

$$F_s = -\frac{0.5Q_{inv.} + Q_{depl}}{\varepsilon_s} \qquad (2)$$

where $Q_{depl} = -[2\varepsilon_s N_b (q\phi_s - k_B T)]^{1/2}$ is the depletion layer charge ($\phi_s$ denotes the surface potential) and:

$Q_{inv.}$ is the total inversion layer charge density

$Q_{inv.} = -q\sum_{ij} N_{ij}$, $N_{ij}$ are sub band occupation factors obtained from Fermi-Dirac statistics to be:

$$N_{ij} = \int_{E_{IJ}}^{\infty} D_j(E) f(E) dE \qquad (3)$$

where f (E) is Fermi occupation factor and $D_j(E)$ is two-dimensional density of states of a sub band. All the more densely spaced sub bands lying high in energy above the band edge at the interface may be approximated by a continuous band.

In case of classical description, where the quantization of electron energy is neglected, we use drift diffusion transport model description

of the semiconductor region. The current density equations or charge transport models are usually obtained by applying approximations and simplifications to the Boltzmann Transport Equation. These assumptions can result in a number of different transport models such as the drift-diffusion transport model, the energy balance transport model or the hydrodynamic transport model.

The simplest model of charge transport that is useful is the drift-diffusion model. Until recently, the drift-diffusion model was adequate for nearly all devices that were technologically feasible. The drift-diffusion approximation, however, becomes less accurate for smaller feature sizes. More advanced energy balance and hydrodynamic models are therefore becoming popular for simulating deep submicron devices. ATLAS supplies both drift-diffusion and advanced transport models.

**II.1. Drift Diffusion Transport Model**

Derivation based on Boltzmann transport theory has shown that the current density in the continuity equations may be approximated by a drift diffusion model [16]. In this case, the current densities are expressed in terms of quasi-Fermi levels $\phi_n$ and $\phi_p$ as:

$$J_n = -q\mu_n n\nabla\phi_n \tag{4}$$

$$J_p = -q\mu_p n\nabla\phi_p \tag{5}$$

where $\mu_n$ and $\mu_p$ are electron and hole mobility. The quasi-Fermi levels are then linked to the carrier concentration and potential through the two Boltzmann approximations:

$$n = n_{ie}\exp[\frac{q(\Psi-\phi_n)}{kT_L}] \tag{6}$$

$$n = n_{ie}\exp[\frac{-q(\Psi-\phi_p)}{kT_L}] \tag{7}$$

where $n_{ie}$ is the effective intrinsic concentration and $T_L$ is the lattice temperature. These two equations may then be re-written to define the quasi-Fermi potentials:

$$\phi_n = \psi - \frac{kT_L}{q}\ln\frac{n}{n_{ie}} \tag{8}$$

$$\phi_p = \psi + \frac{kT_L}{q}\ln\frac{p}{n_{ie}} \tag{9}$$

By substituting these equations into the current density expressions, the following adapted current relationships are obtained

$$J_n = qD_n\nabla n - qn\mu_n\nabla\psi - \mu_n n(kT_L\nabla(\ln n_{ie})) \tag{10}$$

$$J_p = -qD_p\nabla p - qp\mu_p\nabla\psi + \mu_p p(kT_L\nabla(\ln n_{ie})) \tag{11}$$

The final term accounts for the gradient in the effective intrinsic carrier concentration, which takes account of band gap narrowing effects. Effective electric fields are normally defined whereby:

$$E_n = -\nabla(\psi + \frac{kT_L}{q}\ln n_{ie}) \tag{12}$$

$$E_p = -\nabla(\psi - \frac{kT_L}{q}\ln n_{ie}) \tag{13}$$

which then allows the more conventional formulation of drift-diffusion equations to be written. This derivation of the drift-diffusion assumes that the Einstein relationship holds. In case of Boltzmann statistics this corresponds to:

$$J_n = qn\mu_n E_n + qD_n\nabla n \tag{14}$$

$$J_p = qp\mu_p E_p + qD_p\nabla p \tag{15}$$

$$D_n = \frac{kT_L}{q}\mu_n \tag{16}$$

$$D_p = \frac{kT_L}{q}\mu_p \tag{17}$$

If Fermi Dirac statistics are assumed for electrons, Equation (13) becomes

$$D_n = \frac{(\frac{kT_L}{q}\mu_n)F_{1/2}\left\{\frac{1}{kT_L}[\varepsilon_{Fn}-\varepsilon_C]\right\}}{F_{-1/2}\left\{\frac{1}{kT_L}[\varepsilon_{Fn}-\varepsilon_C]\right\}} \quad (18)$$

where $F_\alpha$ is the Fermi-Dirac integral of the order $\alpha$ and $\varepsilon_{Fn}$ is given by $-q\varphi_n$. An analogous expression for holes with Fermi-Dirac statistics will be

$$D_p = \frac{(\frac{kT_L}{q}\mu_p)F_{1/2}\left\{\frac{1}{kT_L}[\varepsilon_{Fp}-\varepsilon_v]\right\}}{F_{-1/2}\left\{\frac{1}{kT_L}[\varepsilon_{Fp}-\varepsilon_v]\right\}}. \quad (19)$$

### II.2. Energy Balance Transport Model

The conventional drift-diffusion model of charge transport model neglects non-local transport effects such as velocity overshoot, diffusion associated with the carrier temperature and the dependence of impact ionization rates on carrier energy distributions. These phenomenons can have a significant effect on the terminal properties of nanoscale devices. The energy balance transport model follows the derivation by Stratton [13-14] which is derived starting from the Boltzmann Transport Equation. The energy balance model adds continuity equations for the carrier temperatures and treats mobility and impact ionization coefficients as functions of the carrier temperatures rather than functions of local electric field. The energy balance transport model introduces two new independent variables $T_n$ and $T_p$, the carrier temperature for electrons and holes. A higher order solution to the general Boltzmann Transport Equation consists of an additional coupling of the current density to the carrier temperature, or energy. The current density expressions from the drift-diffusion model are modified to include this additional physical relationship. The electron current density and energy flux densities are then expressed:

$$J_n = -qD_n\nabla n - qn\mu_n\nabla\psi - qnD_n{}^T\nabla T_n \quad (20)$$

$$J_p = -qD_p\nabla p - qp\mu_p\nabla\psi - qpD_p{}^T\nabla T_p \quad (21)$$

$$S_n = -K_n\nabla T_n - \left(\frac{k\delta_n}{q}\right)J_nT_n \quad (22)$$

$$S_p = -K_p\nabla T_p - \left(\frac{k\delta_p}{q}\right)J_pT_p \quad (23)$$

where $T_n$ and $T_p$ represents the electron hole carrier temperature and $S_n$ and $S_p$ are the flux of energy from the carrier to the lattice.

### III. DEVICE STRUCTURE SIMULATED

The structure of the Fully Depleted Double Gate SOI MOSFET used in this paper is schematically presented in fig. 1.

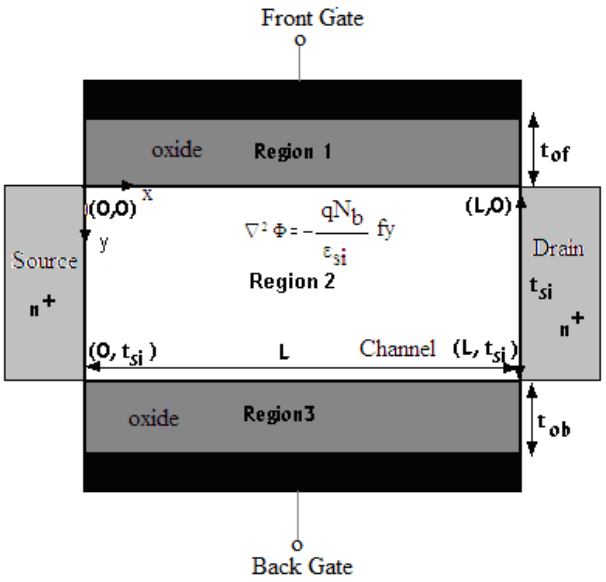


**Fig. 1:** Schematic diagram of a Fully Depleted Double Gate Nanoscale SOI MOSFET.

We consider N channel devices. This symmetric structure is characterized by two identical Aluminum metal gates connected together. The thickness of p-type doped silicon ($t_{si}$) is 6nm, channel length (L) for device is 10nm, doping level of p-type silicon channel i.e. $N_b$ = $1x10^{17}$ $m^{-3}$, top/bottom gate oxide thickness i.e. $t_{oxf}$ = $t_{oxb}$ = 1.5nm. The source/drain regions are uniformly doped at a

level of $1x10^{20}$ $m^{-3}$. The same gate voltage $V_{gs}$ is applied to both gates. Low field mobility ($\mu_{no}$) is $750cm^2/Vs$ and all simulations have been done at room temperature i.e. at T=300 K.

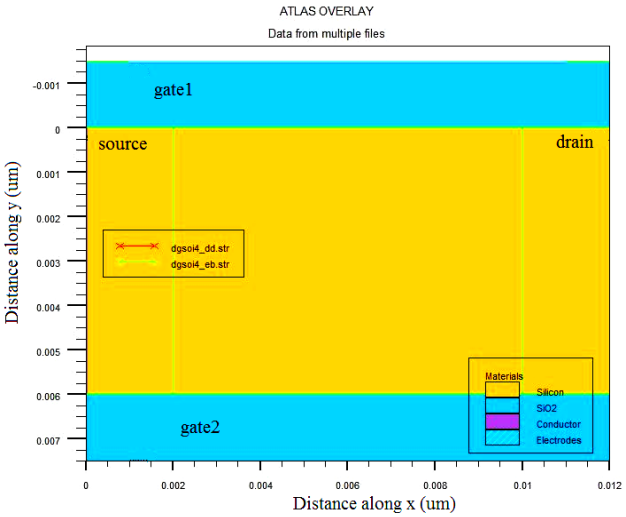


**Fig. 2:** Structure created on deckbuild of ATLAS device simulator for Drift-Diffusion Transport Model and Energy Balance Transport Model with channel length L=10nm, source/drain (n+) doping $1\times10^{20}\,m^{-3}$, Aluminum gates with work function 4.10 electron Volt, top/bottom gate oxide thickness i.e. $t_{oxf}$ = $t_{oxb}$ = 1.5nm, doping level of p-type silicon channel $N_b$ = $1x10^{17}m^{-3}$ and thickness of silicon channel $t_{si}$ = 6nm.

Figure 2 shows the structure created on deckbuild of ATLAS device simulator for drift-diffusion transport model and energy balance transport model respectively. Figure 3 shows comparison of drain current ($I_d$) versus gate to source voltage ($V_{gs}$) characteristic for our device employed with drift-diffusion transport model and energy balance transport model. Here, electrical characteristics $I_d(V_{gs},V_{ds})$ for a double gate fully depleted nanoscale SOI MOSFET are investigated. The drain current as a function of gate voltage is plotted in figure 3. The results obtained from energy balance transport model are compared to the drift-diffusion transport model approach. Electrical characteristics as predicted by conventional drift-diffusion transport model vary from the one obtained by quantum effect based model i.e. energy balance transport model in our case. Due to extremely short channel of the modeled device, the carrier behavior within the channel is expected to be quasi-ballistic, thus allowing a strong velocity overshoot to be reached. As expected, the energy balance transport model gives higher currents compared with the drift-diffusion transport model, due to the electron velocity overshoot with in the channel.

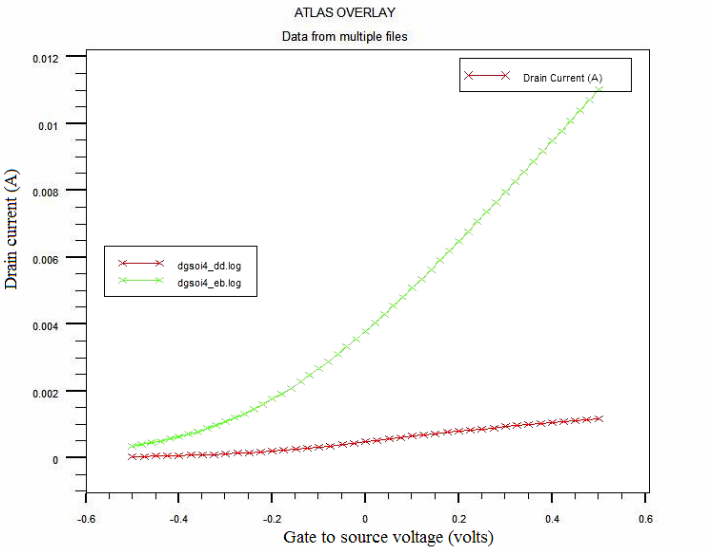


**Fig. 3:** The simulated output characteristics showing comparison of $I_{ds}$ versus $V_{gs}$ for Drift-Diffusion Transport Model and Energy Balance Transport Model.

Figure 4 shows structure created on deckbuild of ATLAS showing mobility of simulated device with channel doping $N_b$ = $1x10^{17}$ $m^{-3}$. Simulated output characteristic created on deckbuild of ATLAS showing mobility of simulated device with channel doping $N_b$ = $1x10^{17}$ $m^{-3}$ is shown in figure 5. Figures 6 and 7 show structure and simulated output characteristic respectively created on deckbuild of ATLAS showing mobility of simulated device with channel doping $N_b$ = $5x10^{18}$ $m^{-3}$. Recent studies on sub 100nm bulk MOSFETs have made it clearer that a higher impurity concentration ($N_b \geq 5x10^{18}$ $m^{-3}$.) in the channel is indispensable in suppressing short channel effects. This puts a strong limitation on device scaling. The advantage of Fully Depleted SOI MOSFETs, especially a double gate structure is that it can provide high short channel effect

(SCE) immunity with a low concentration channel (lightly doped). Analyzing the performance of device on the basis of varying the doping concentration in the channel, it is observed that lower concentration (fig. 5) in double gate fully depleted SOI MOSFET results in higher mobility and therefore better performance whereas high concentration (fig. 7) degrades carrier mobility thereby resulting in poor device performance.

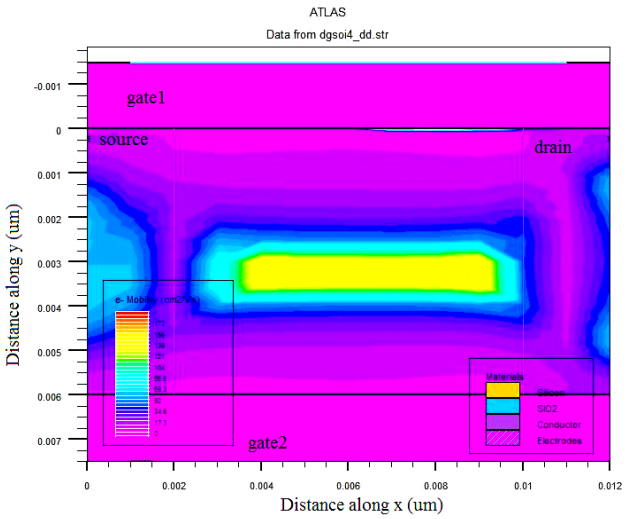


**Fig. 4:** Structure created on deckbuild of ATLAS device simulator with channel length L =10nm, source/ drain (n+) doping of $1x10^{20}$ $m^{-3}$, Aluminum gates, with work function of 4.10 eV, top/bottom gate oxide thickness i.e. $t_{oxf} = t_{oxb}$ = 1.5nm, doping level of p-type silicon channel i.e. $N_b = 1x10^{17}$ $m^{-3}$ and thickness of silicon channel $t_{si}$ = 6nm.

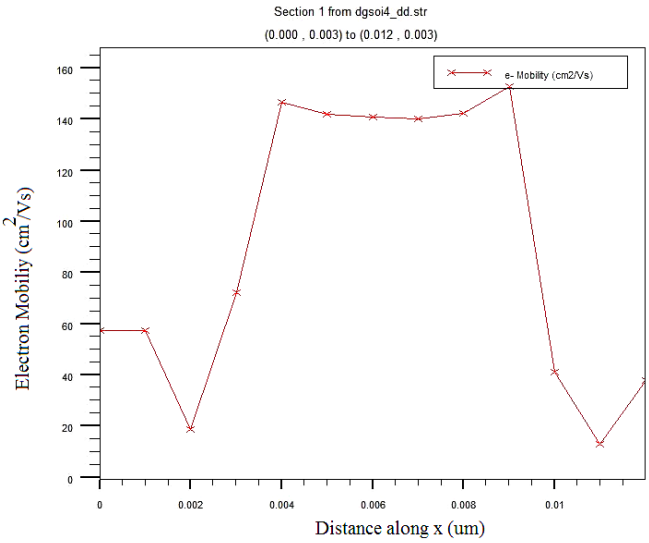


**Fig. 5:** The simulated output characteristics showing variation of mobility with distance along the channel for channel doping $N_b = 1x10^{17}$ $m^{-3}$.

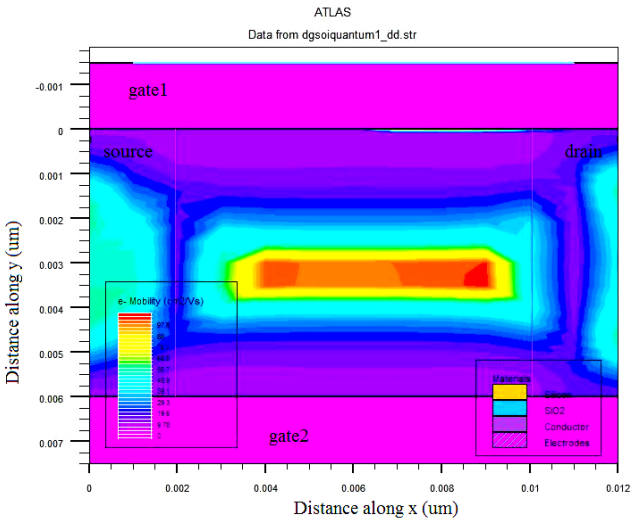


**Fig. 6:** Structure created on Deckbuild of ATLAS device simulator with doping level of p-type silicon channel i.e. $N_b = 5x10^{18}$ $m^{-3}$. Channel length L = 10nm, source/drain (n+) doping of $1x10^{20}$ $m^{-3}$ , Aluminum gates, with work function of 4.10 eV, top/bottom gate oxide thickness i.e. $t_{oxf} = t_{oxb}$ = 1.5nm, and thickness of silicon channel $t_{si}$ is 6nm.

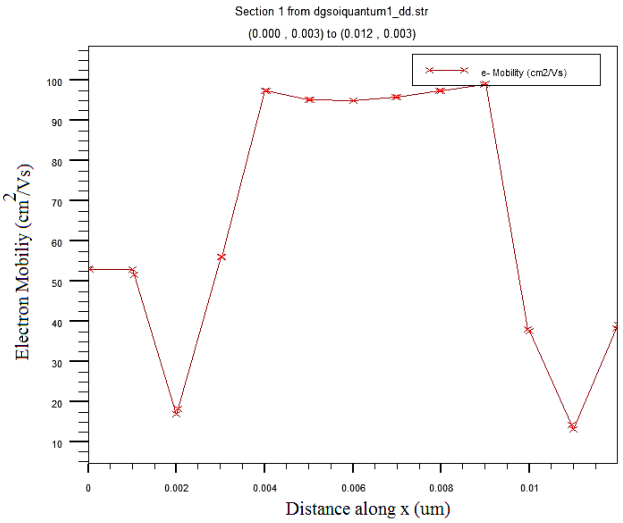


**Fig. 7:** The simulated output characteristics showing variation of mobility with distance along the channel for channel doping $N_b = 5x10^{18}$ $m^{-3}$.

## IV. CONCLUSION

We present results of Fully Depleted Double Gate SOI Deca Nanometer MOSFET performance carried out using ATLAS T-CAD

device simulator. Influence of non local transport effects is of prime importance for correct evaluation of electrical characteristics of ultrascaled double gate SOI MOSFETs. Conventional drift-diffusion transport model is not efficient in capturing these non-static effects. Energy balance transport model accounts for non local transport effects by including impact ionization coefficient as a function of temperature, therefore energy balance transport model proves to be more accurate compared to drift-diffusion model. Further device simulations were carried out with two different doping concentrations in silicon channel. As expected, simulation results confirm the fact that Fully Depleted Double Gate SOI MOSFETs with low impurity concentration provides better performance.

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