

NUMERICAL ANALYSIS STUDY OF THE EFFECTS OF BACKSCATTERING COEFFICIENT ON ELECTRICAL PERFORMANCE OF DOUBLE-GATE NANO-MOSFET

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ABSTRACT

This paper has investigated and compared the simulated and computed electrical characteristics of 10 nm double-gate (DG) nano-MOSFET with and without carrier backscattering. The electrical parameters thus studied include Ballistic Enhancement Factor (BEF), on-state ballistic drain current I_{ds} , 2D electron density Q_i and electron velocity v . BEF values with and without backscattering coefficients are 2.065 and 2.149, respectively, because injection velocity reduced when considering backscattering. Average electron velocity near the beginning of the device channel has been found to reduce from $4.131 \times 10^5 \text{ ms}^{-1}$ to $1.186 \times 10^5 \text{ ms}^{-1}$ with the inclusion of the backscattering phenomenon. The 2D electron density with and without backscattering coefficients are $3.927 \times 10^{16} \text{ m}^{-2}$ and $3.850 \times 10^{16} \text{ m}^{-2}$, respectively. The increment is because backscattered electrons and injected electrons superimposed and interfered with each other in the channel due to the wave nature of electrons occurrence in nanometer transistors. There are two current equations studied in this paper. The first is on flux theory, and the other is on the product of electron concentration and velocity. The first method showed a current reduction from $2.548 \times 10^3 \mu\text{A}/\mu\text{m}$ to $2.497 \times 10^3 \mu\text{A}/\mu\text{m}$. The second way also showed an approximate reduction from $2.548 \times 10^3 \mu\text{A}/\mu\text{m}$ to $2.497 \times 10^3 \mu\text{A}/\mu\text{m}$ after minor modification in modeling. Both ways indicate that electrons are backscattered to the source by the potential barrier at the beginning of the channel, thereby reducing the number of electrons reaching the drain. In conclusion, backscattering is a physical phenomenon which can't be ignored in describing electron transport in DG nano-MOSFETs.

Keywords: Simulation, theoretical calculation, transport model, nanometer, ballistic, quantum effects

INTRODUCTION

In classical bulk MOSFETs, the carriers transport model involved is a drift-diffusion equation, whereas, in nanoscale nano-MOSFETs, the carriers transport model is mainly ballistic quantum mechanical in nature [1]-[4]. Device scientists can use Technology Computer-Aided Design (TCAD) software to study and examine the transport models of both cases [5]-[6]. The main obstacle in using TCAD is the development of relevant carrier transport models software codes which are normally complex and sophisticated, especially when dealing with nanodevice quantum models. The

quantum numerical models must take into account quantum confinement in the device channel and non-equilibrium transport physics, which comprise all related scattering mechanisms [7]-[9]. Currently, there are two main physical models used in simulating nanotransistors. The first one is applying Multi Subband Monte Carlo Method for solving Boltzmann Transport Equation, but this is not the focus of this paper. The second approach is applying Non-Equilibrium Green's Function (NEGF) formalism to solve the Schrodinger equation, which rigorously captures the wave property

of carriers, but scattering mechanisms are difficult to incorporate into this second method, especially when devices are downscaled to nanometer regimes [10]-[12]. Backscattering in quantum mechanical limits is one crucial parameter concerning the scattering events [13]-[18]. Backscattering must be included in numerical transport models for nanotransistors in order to accurately evaluate the electrical performance of the nanodevices under investigation before the nanotransistors can be commercialized to design logic circuits and electronic systems [19]-[24]. This is the reason why this study is being carried out.

DEVICE DESIGN

The symmetric 10 nm DG nano-MOSFET device structure used in this simulation study is shown in Figure 1.

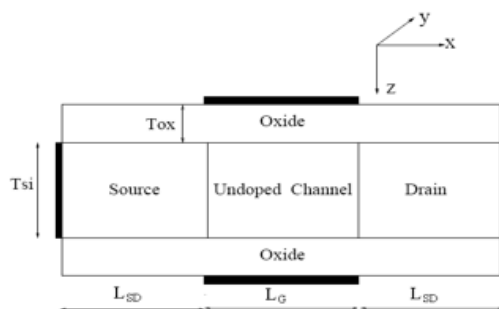


Figure 1 Device structure diagram

The device simulation software used is free online nanoMOS which applies NEGF formalism to solve the Schrodinger equation. The semiconductor material used is Silicon (Si). Si is chosen because it is the most abundant material on the earth and thus eliminating any doubt about availability. Moreover, the fabrication technology of Si is mature nowadays. The device structural simulation parameters settings are listed in Table 1. The device parameters in Table 1 are chosen such that the electrons in the channel have quantum mechanical properties instead of possessing particle nature properties as in classical bulk MOSFETs. Wafer orientation is (001) with translational direction [100]. This Si (001) wafer orientation is chosen such that the device coordinate axes will be in the same directions as the constant-energy ellipsoids of the conduction band. This situation will facilitate quantum mechanical treatment and simplify the computation of electron transport in n-MOSFETs. These criteria are not satisfied in other wafer orientations, such as (111).

Table 1 Device simulation parameters settings

Simulation Parameters Setting of Double-Gate nano-MOSFET	
Drain-to-Source Voltage Bias (VDS)	0.60 V
Gate-to-Source Voltage Bias (VGS)	0.60 V
Threshold Voltage (VT)	0.20 V
Ambient Temperature	300 K
Source/Drain Doping Concentration (ND)	$1 \times 10^{20} \text{ cm}^{-3}$
Body Doping Concentration	0 cm^{-3}
Silicon Channel Thickness (TSi)	1.5 nm
Source/Drain Overlap	0 nm
Source Length/Drain Length (LSD)	7.5 nm
Channel Length (L)	10 nm
Top/Bottom Oxide Insulator Thickness (TOX)	1.5 nm
Top/Bottom Insulator Relative Dielectric Constant	3.9
Longitudinal Relative Electron Mass Ratio (ml)	0.98
Transverse Relative Electron Mass Ratio (mt)	0.19
Channel Body Relative Dielectric Constant	11.7
Top/Bottom Gate Contact Work Function	4.188 eV
Silicon Conduction Band Valleys	unprimed
Number of Subbands	1

REVIEW OF THE TRANSPORT THEORY OF NANO-MOSFET

Transport Model without Backscattering

This model is proposed by Natori [25] with two assumptions. Firstly, drain and source are considered

ideal reservoirs of electrons in equilibrium conditions. Secondly, the gate controls the potential barrier perfectly, so Short Channel Effects (SCEs) can be neglected. According to this model, the semiclassical flux of electrons emitted from the source, F_s^+ in equilibrium in the Si channel is computed easily as,

$$F_s^+ = \frac{(2kT)^{3/2}}{\pi^2 \hbar^2} \left[\sum i\sqrt{m_{cL}} F_{1/2} \left(\frac{E_{Fs} - E_i^L}{kT} \right) + \sum i\sqrt{m_{cT}} F_{1/2} \left(\frac{E_{Fs} - E_i^T}{kT} \right) \right] \quad (1)$$

where, $m_{cL} = m_t$, $m_{cT} = (m_l^{1/2} + m_t^{1/2})^2$, i is the subband index E_i^L (resp. E_i^T) unprimed (resp. primed) subband energies

On the other hand, the semiclassical flux of electrons emitted by drain, F_d^- is

$$F_d^- = \frac{(2kT)^{3/2}}{\pi^2 \hbar^2} \left[\sum i\sqrt{m_{cL}} F_{1/2} \left(\frac{E_{Fd} - E_i^L}{kT} \right) + \sum i\sqrt{m_{cT}} F_{1/2} \left(\frac{E_{Fd} - E_i^T}{kT} \right) \right] \quad (2)$$

where, $E_{Fd} = E_{Fs} - qV_{DS}$ and $F_{1/2}$ is the Fermi-Dirac Integral of order $1/2$.

$$F_s^+ = \frac{(2kT)^{3/2}}{\pi^2 \hbar^2} \left[\sum i\sqrt{m_{cL}} F_{1/2} \left(\frac{E_{Fs} - qV_{DS} - E_i^L}{kT} \right) + \sum i\sqrt{m_{cT}} F_{1/2} \left(\frac{E_{Fs} - qV_{DS} - E_i^T}{kT} \right) \right] \quad (3)$$

The above model is formulated in the quantum limit regime and can be generalized in the more general case of a multi-subband inversion layer for various materials with arbitrary wafer orientation.

In a full ballistic regime with charge distribution in k-space, when the positive k states of the conduction band are occupied by electrons injected by source reservoirs, the electron density, N_s^+ flowing from source to drain is given by:

$$N_s^+(E_{Fs}) = \left[\sum i \frac{1}{2} \frac{m_{DL}}{\pi \hbar^2} kT F_0 \left(\frac{E_{Fs} - E_i^L}{kT} \right) + \sum i \frac{1}{2} \frac{m_{DT}}{\pi^2 \hbar^2} kT F_0 \left(\frac{E_{Fs} - E_i^T}{kT} \right) \right] \quad (4)$$

where $m_{dL} = 2m_t$, $m_{dT} = (m_l m_t)^{1/2}$ and F_0 is the Fermi-Dirac Integral of order zero. Whereas the negative k states of the conduction band are populated by electrons emitted by the drain and the electron density, N_d^- flowing from drain to source is expressed as,

$$N_d^-(E_{Fs}, V_{DS}) = \left[\sum i \frac{1}{2} \frac{m_{DL}}{\pi \hbar^2} kT F_0 \left(\frac{E_{Fs} - qV_{DS} - E_i^L}{kT} \right) + \sum i \frac{1}{2} \frac{m_{dT}}{\pi^2 \hbar^2} kT F_0 \left(\frac{E_{Fs} - qV_{DS} - E_i^T}{kT} \right) \right] \quad (5)$$

For a properly designed nano-MOSFET without SCEs, the total charge at the virtual source is constant when

a voltage bias V_{DS} is applied between the source and drain. The total charge density, Q_i is given by:

$$Q_i = qN_s^+(E_{Fs}) + qN_d^-(E_{Fs}, V_{DS}) \quad (6)$$

In non-equilibrium conditions, there is a difference of qV_{DS} between the Fermi level between the source and drain. At last, the net current flow from source to drain is simply expressed by:

$$I_d^{BAL} = q(F_s^+ - F_d^-) \quad (7)$$

The injection velocity, V_{inj} is defined as the ratio between the flux of electrons injected by the source into the channel divided by the corresponding electron density, stated as:

$$V_{inj} = \frac{F_s^+}{N_s^+} \quad (8)$$

In a high drain bias condition, that is high field situation, where nano-MOSFET is at on-state, the drain is unable to emit electrons capable of reaching the source, and the current equation is simply given by:

$$I_d^{BAL} \sim Q_i V_{inj} \quad (9)$$

The product of electron density and average electron velocity actually forms this current equation.

When comparing electron transport in nano-MOSFET with those models in bulk MOSFET, one parameter of great interest to device engineers is BEF which is given by:

$$BEF_{BAL} = \frac{V_{inj}}{V_{sat}} \quad (10)$$

where V_{sat} is the saturation velocity. In other words, BEF is simply the ratio between ballistic current and drift-diffusion current.

A complete understanding of the above theories requires extensive research and sophisticated tools. All the above equations are expressed without considering backscattering [26]-[27].

Transport Model with Backscattering

Lundstrom has modified the transport model without backscattering in the previous subsection with the

flux theory concept to account for backscattering. The important parameter of this method is the introduction of the backscattering coefficient, r . This parameter is defined as the ratio between the flux of electrons reinjected to the source by scattering and the flux of electrons emitted by the source. The schematic diagram of this phenomenon is shown in Figure 2 as adopted from the reference [28].

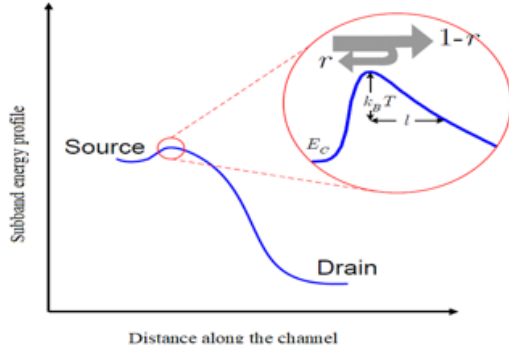


Figure 2 Diagram showing the backscattering mechanism

Basically, the value of backscattering is between 0 and 1. It depends on the potential barrier within the channel, gate bias, drain bias and scattering mechanisms. In other words, the backscattering ratio is given by the following equation [29]:

$$r = \frac{l}{(l + \lambda)} \quad (11)$$

where the backscattering mean free path of carriers is λ , critical length of scattering is l . The equations in the previous subsection can be improved by using this backscattering coefficient. So, Equation 6 becomes Equation 12, Equation 7 becomes Equation 13, Equation 9 becomes Equation 14 and finally, Equation 10 becomes Equation 15.

$$Q_i = qN_s^+(E_{Fs})(1+r(V_{DS})) + qN_d^-(E_{Fs}, V_{DS})(1-r(V_{DS})) \quad (12)$$

$$I_d^{QBAL} = q[F_s^+ - rF_s^+ - (1-r)F_d^-] \quad (13)$$

$$I_{dsat}^{QBAL} = \frac{(1-r_{sat})}{(1+r_{sat})} Q_i V_{inj} \quad (14)$$

$$BEF_{QBAL} = \frac{1-r_{sat}}{1+r_{sat}} \frac{V_{inj}}{V_{sat}} \quad (15)$$

Backscattering determines the upper limit of average electron velocity at the beginning of the channel, $\langle v(0) \rangle$. Under high drain bias, this average electron velocity can be related to backscattering according to the following equation:

$$\langle v(0) \rangle \approx \frac{(1-r)}{(1+r)} v_T \quad (16)$$

where v_T is thermal velocity given by:

$$v_T = \sqrt{\frac{2kT}{\pi m_i^*}} \quad (17)$$

with m_i^* is the effective transverse mass.

Due to the high electric field caused by high drain bias and strong velocity overshoot, electron transport at the drain end of the channel is determined by how quickly electrons are transported across a short low-field region near the source terminal of the channel. This crucial region is called the “kT-layer”, as shown in Figure 2 because it is approximately the distance where the channel potential is reduced by $k_B T/q$. The on-state drain current is controlled by scattering within this kT-layer. The scattering at the drain end of the channel can be ignored since it has just an indirect effect. For a well-designed nano-MOSFET, such as the structure studied in this paper, the kT-layer has a length of about one mean free path. This implies that quasi-ballistic electron transport occurs across this kT-layer.

Backscattering has to be included in the electron transport models because, in practical semiconductor nanodevices, such as DG nano-MOSFET in this study, scatterings always exist in the channel, so incorporating backscattering can accurately explain electrical performance in the real situation by equations.

RESULTS AND DISCUSSION

From Equation 11, the backscattering coefficient r is

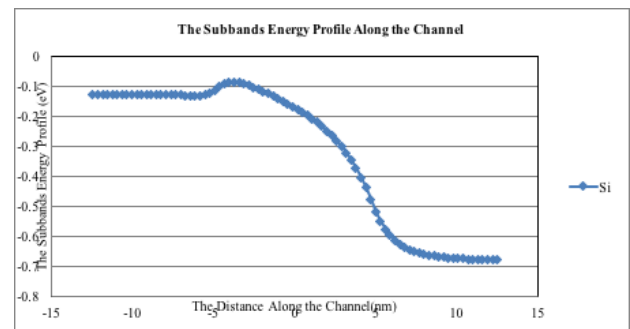


Figure 3 Subband energy profile along the channel direction

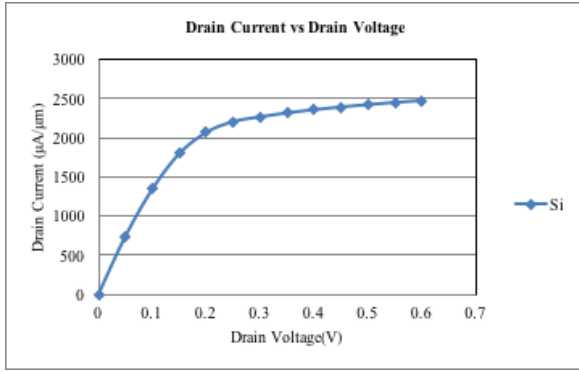


Figure 4 Drain current against drain voltage curve

0.02, where the detailed calculation can be found in reference [30]. Figures 3 and 4 show the simulation output plot of the subband energy profile and drain current versus drain voltage graph, respectively.

The conduction subband simulated is an unprimed subband with one valley. Since the energy level splitting is much larger than the thermal voltage in ultrathin nano-MOSFET, electrons can only populate the bottom subband without jumping to higher levels. It is enough to simulate and study only one unprimed subband, as in this project. From Figure 3, Equations 1 and 3 are calculated to be $1.590 \times 10^{22} \text{ cm}^{-1} \text{ s}^{-1}$ and $8.239 \times 10^{12} \text{ cm}^{-1} \text{ s}^{-1}$, respectively. Using Equations 7 and 13, the drain current without and with backscattering are evaluated to be equal to $2.548 \times 10^3 \mu\text{A}/\mu\text{m}$ and $2.497 \times 10^3 \mu\text{A}/\mu\text{m}$, respectively. At high drain bias conditions, using Equations 9 and 14 for the situation without and with backscattering, the drain current is calculated to be $2.548 \times 10^3 \mu\text{A}/\mu\text{m}$ and $2.497 \times 10^3 \mu\text{A}/\mu\text{m}$,

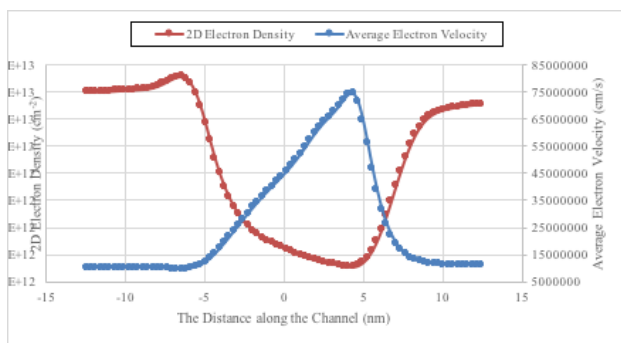


Figure 5 2D Electron density and average electron velocity along the channel

respectively. These two current models exhibited a reduction of drain current when the backscattering coefficient was introduced to the current models because electrons are backscattering by potential

barriers. Equations 9 and 14 use the current model of the product between electron concentration and electron velocity, as shown in Figure 5 [31].

Refer to Figure 5 for the 2D electron density curve. Using Equations 4 and 5, from Figure 3, N_s^+ and N_d^- are computed to be $3.850 \times 10^{16} \text{ m}^{-2}$ and $5.872 \times 10^7 \text{ m}^{-2}$, respectively. Summing these two values produces the 2D electron density of $3.850 \times 10^{16} \text{ m}^{-2}$, which corresponds to a charge density of $6.167 \times 10^{-3} \text{ cm}^{-2}$ at the centre of the nano-MOSFET. From Figure 5, the simulated value of electron density is $3.4 \times 10^{16} \text{ m}^{-2}$. As stated in Equation 12, when backscattering is included, the 2D electron density is $3.927 \times 10^{16} \text{ m}^{-2}$, corresponding to a charge density of $6.290 \times 10^{-3} \text{ cm}^{-2}$. The slight increment, as observed, is considered due to interference between backscattered electrons and injected electrons with each other in the channel region. The electron density in the channel is low compared to those in the source and drain because electrons injected from the source are treated quantum mechanically and can be reflected back into the source, therefore, electron density gradually decreases toward the drain in the channel. Electrons are also injected from the drain but can be ignored at high drain bias. Figure 6 shows the plot of 2D electron density along the channel with the subband energy profile at the secondary axis.

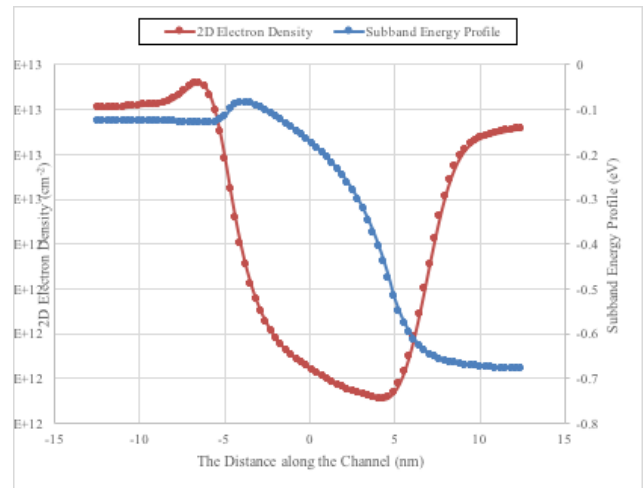


Figure 6 2D electron density and subband energy profile along the channel

After computing F_s^+ and N_s^+ , the injection velocity V_{inj} which is obtained from Equation 8, is equal to $4.131 \times 10^5 \text{ ms}^{-1}$. Figure 7 shows the average electron velocity along the channel plotted with the subband energy profile at the secondary vertical axis.

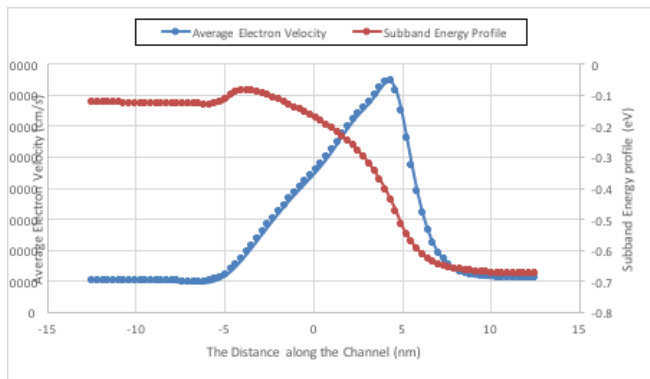


Figure 7 Average electron velocity and subband energy profile along the channel

From the figure, the electron saturation velocity at the peak barrier is $1.922 \times 10^5 \text{ ms}^{-1}$; hence, from Equation 10, BEF is 2.149 without a backscattering coefficient, while from Equation 15, BEF with a backscattering coefficient is 2.065. Since BEF is a measure of current enhancement and so, as expected, the drain current with a backscattering coefficient will be lower as a result of lower BEF.

In Figure 7, the low energy band between 5 nm and 12.5 nm is at the region of the drain reservoir where electrons are in thermal equilibrium with an average velocity of around $1 \times 10^7 \text{ cms}^{-1}$, as can be observed from Figure 7. The source terminal is biased at 0.00 V, and the drain terminal is biased at 0.60 V. Therefore, the quasi-Fermi level at the source is expected to equal 0 eV, which is around -0.1 eV as taken from the graph. Since only an electron is considered in this simulation (no hole is involved), the Fermi level at the drain is around -0.7 eV. As the electrons injected by the source, which are not reflected by potential barrier, travel to the drain due to a high electric field caused by drain bias, electrons achieved high average velocity before they enter the drain reservoir.

The thermal velocity, as calculated with Equation 17, is $1.234 \times 10^5 \text{ ms}^{-1}$. Backscattering will affect the electron velocity at "kT-layer", which is located near the source at the beginning of the channel. From Equation 16, this velocity $v(0)$ is roughly $1.186 \times 10^5 \text{ ms}^{-1}$, which is lower than thermal velocity. Since electron transport across the kT-layer determines the current flow, there is a decline in drain current when considering $v(0)$ with a backscattering coefficient [32].

CONCLUSION

Electron transport models in ultrathin and ultrashort nano-MOSFETs are quantum mechanically in nature. These models must include scattering mechanisms, such as electron-phonons and electron-impurities scattering, to accurately describe the carrier transport through the channel. In this paper, due backscattering reflection from the subband energy potential barrier has been shown to potentially influence the performance accuracy of nano-MOSFET electrical characteristics such as drain current, electron density and average electron velocity. There is a discrepancy in performance between the transport model with and without backscattering. Therefore, all nano-MOSFET devices must be evaluated electrically with correct transport models before these nanotransistors can be commercialised to design logic circuits and electronic systems.

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