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Variation Effect of Silicon Film Thickness on Electrical Properties of NANO-MOSFET

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ABSTRACT

Owing to the fact that metal oxide semiconductor field effect transistors (MOSFETs) can be effortlessly assimilated into ICs, they have become the heart of the growing semiconductor industry. The need to procure low power dissipation, high operating speed and small size requires the scaling down of these devices. This fully serves the Moore's Law. But scaling down comes with its own drawbacks which can be substantiated as the Short Channel Effect. The working of the device deteriorates owing to SCE. In this work numerical simulations have been performed to investigate the electronic transport through the Silicon (Si) channel of four terminal Nano-MOS namely; drain, source, top gate and bottom gate. Also, the thickness of Silicon film channel is varied from 1.5 nm, 2.5 nm, 3.5 nm, 4.5 nm and 5.5 nm with other structural dimensions remain unchanged. The simulation is carried out at room temperature (RT) using Nano-MOS simulating software. Three models have been presented such as; ballistic transport using Green's function approach, ballistic transport using semi classical approach, and drift diffusion transport. The electrical properties such as 2D electron density of the sub bands, sub bands energy profile and drain current - gate voltage (I_{DS}-V_{GS}) have been plotted to compare the performance of these three transport models. From the simulation analysis, the drift diffusion transport model shows low performance in comparison with the two other models, maybe due to the electron gas scattering encountered during the transport through Si channel. Meanwhile, Green's function approach and semi classical approach shows almost similar results with high performance.

KEYWORDS
Ballistic transport, Drift Diffusion Transport, MOSFET, Nanoscale, Semi Classical Transport.

1. INTRODUCTION

The numerical modeling of open quantum devices has become an indispensable tool to understand transport physics of semiconductor devices scaled down to nano-meters regime [1]. Non-equilibrium Green's function (NEGF) method is a comprehensive approach to elaborate the quantum transport under external potential bias. Semi-classical approach applies the techniques of Boltzmann kinetic to explain the electron transport. Both of these models are ballistic in nature. Meanwhile, drift diffusion transport has scattering [2].

In 1965 Gordon Moore predicted that the number of transistors per chip would quadruple every three years [3]. The channel length which is an important dimension has been shrinking continuously and will continue to decrease [4]. The reason behind this continuous miniaturizing is to have high speed devices in very large scale integrated circuits. As we are scaling down the size of device, channel length of the device shrinks and this nearness between source and drain reduces the gate electrodes controlling influence on the potential distribution and current flow in the channel which in result deteriorates device performance. The double-gate (DG) transistor is considered one of the most promising devices for extremely scaled CMOS technology generations. Indeed, due to a good electrostatic control of the channel by the two gates, it is expected to provide smaller short-channel effects (SCE), near ideal sub-threshold slopes and higher drive currents when compared to single-gate (SG) transistors [5, 6].

2. THEORITICAL BACHGROUND

2.1. Ballistic and Diffusive Carriers Transport Mechanisms

Before the discovery of ballistic carrier transport, the transport mechanism of the conventional MOSFET is mainly “diffusive”, which means that the electron takes a random walk from the source to the drain, traveling in one direction for some length of time before getting scattered into some random direction as sketched in Fig.1.0 below. The mean free path mfp, that an electron travels before getting scattered is typically less than a micrometer (also called a micron = 10^{-3}mm, denoted by µm) in common semiconductors, but it varies widely with temperature and from one material to another [7].

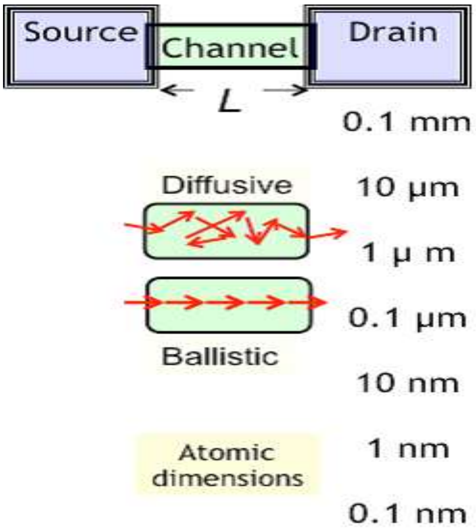

Figure 1.0: Diffusive and Ballistic carriers transport mechanisms

2.2. Transport Equations

Transport equations such as the Boltzmann equation can describe electron dynamic. They determine the dynamics of electron density distribution in response to perturbation such as external electric field and electron density gradient. The electron drift-diffusion equation is given by

$$j_n = qn\mu_n\varepsilon + qD_n\nabla_n = -qn\mu_n\nabla\emptyset + qD_n\nabla_n \qquad (1)$$

Where;

j_n is the electron current density

n is the electron density

μ_n is the electron mobility

D_n is the electron diffusion coefficient

$\emptyset$ is the electric field

ε is the electric potential

2.3. Poisson’s equation

Poisson’s equation is a fundamental equation describing the spatial relationship between a certain electron density distribution and the corresponding electric field. It holds true no matter which transport equation/model we use, so it is a common routine for all simulation options.

$$\nabla^2\emptyset = -\frac{1}{\epsilon}(p - n + N_D^+ - N_A^-) \qquad (2)$$

Where;

$\emptyset$ is the electrical potential

n is the electron density

p is the hole density

N_D^+ is the donor density

N_A^- is the acceptor density

In Nano-MOS, we assume the absence of holes and only treat electrons. Thus,
Poisson’s equation becomes

$$\nabla^2 = -\frac{1}{\epsilon}(-n + N_D^+ - N_A^-) \qquad (3)$$

3. METHODOLOGY

In this paper, online Nano electronic device simulation software, Nano-MOS is used to study the variation effect of silicon film thickness at nano regime, where by five different DG-Nano-MOS with thickness of silicon film channel 1.5, 2.5, 3.5, 4.5 and 5.5nm are simulated respectively with other structural dimensions fixed. The double gate Nano-MOS are simulated using nanoMOS simulation software. Figure 2.0. shows Si double gated MOSFET.

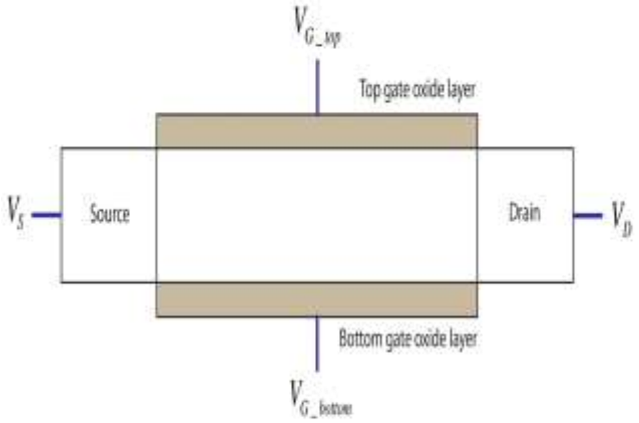

Figure 2.0: Ideal double-gated MOSFET structure

3.1. Nano-MOS Software

The Nano-MOS is a 2D simulator for thin body, fully depleted double gate n-MOSFETs. A choice of three transport models is currently available (drift diffusion, classical ballistic and quantum ballistic). The transport models treat quantum effects in the confinement direction exactly and the names indicate the technique used to account for carrier transport along the channel. Each of these transport models is solved self-consistently with Poisson's equation. Several internal quantities such as sub-band profiles, sub-band areal electron densities, potential profiles and I – V information can be obtained from the source code.

3.2. SIMULATION PROCEDURE:

- The device modelling was done by choosing device type, that is double gate MOSFET.
- Then transport and bias are set by choosing ballistic transport using Green's function approach.
- Then device description such as, source and drain doping concentration, source and drain length, top and bottom gate length etc was also set.
- Then silicon film channel thickness was varied from 1.5nm to 5.5nm.
- The program is then run to obtain results.
- However, steps 2 to 5 was repeated with ballistic transport using semi-classical approach and lastly with drift diffusion transport.

Table 1.0: Input Parameters and their Values

INPUT PARAMETERS	VALUE
Source/drain doping concentration	$1e20/cm^3$
Source/drain overlap	0
source/drain length	7.5nm
source/drain potential fixed	0.6V
Channel length	10nm
Top/ bottom insulator thickness	1.5nm
Top/bottom gate length	10nm
Temperature	300K
Gate voltage step size	0.05V
Silicon film channel thickness	1.5nm – 5.5nm

4. RESULTS AND DISCUSSION

4.1. Simulations Result of 2D Electron Density of Sub-bands along Channel

4.1.1. SIMULATIONS RESULT AT 1.5nm Tsi

The plot of 2D electron density of sub-bands along channel shown in figure 3.0 shows that the three transport models curve have roughly the same outline, except that there are discrepancies in the magnitude of 2D electron density of the sub-bands in the drain reservoir, channel and source reservoir region. The distribution of electron density was almost the same for ballistic transport using Green's function and semi-classical approach, whereas the drift diffusion model has more electron on the channel region due to scattering mechanism.

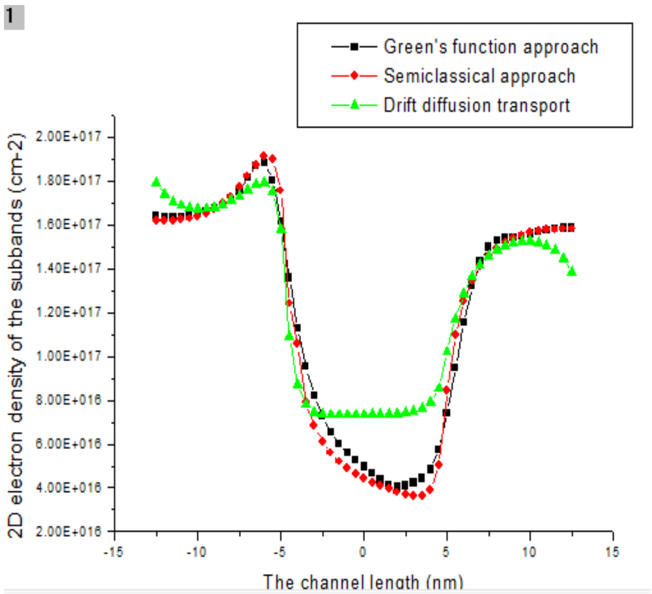

Figure. 3.0: 2D electron density of the sub-bands along channel

4.1.2. SIMULATIONS RESULT AT 2.5nm Tsi

The plot of 2D electron density of sub-bands along channel at 2.5nm Si film thickness shows that the distribution of electron density was almost the same for ballistic transport using Green's function and semi-classical approach while drift diffusion transport has more electron on the channel region and is more than that of 1.5nm.

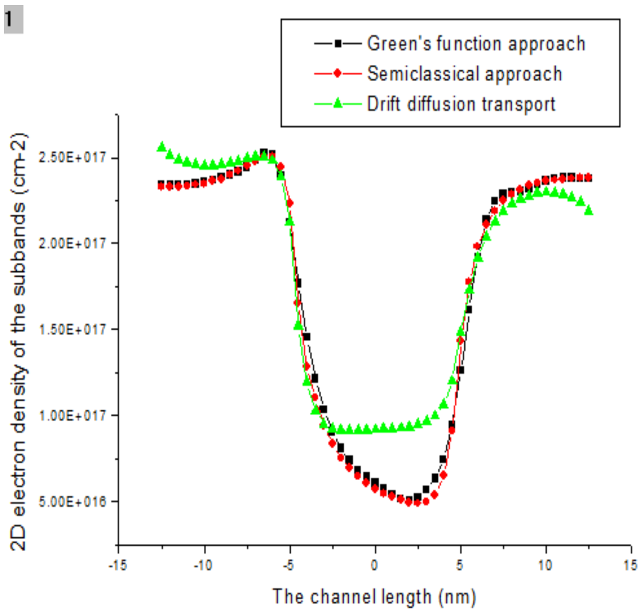

Figure. 4.0 2D electron density of the sub-bands along channel

4.1.3. SIMULATIONS RESULT AT 3.5nm Tsi

The plot of 2D electron density of sub-bands along channel at Si film thickness of 3.5nm shows that the distribution of electron density of Green's function and semi-classical approach are almost the same while drift diffusion has more electron at channel region.

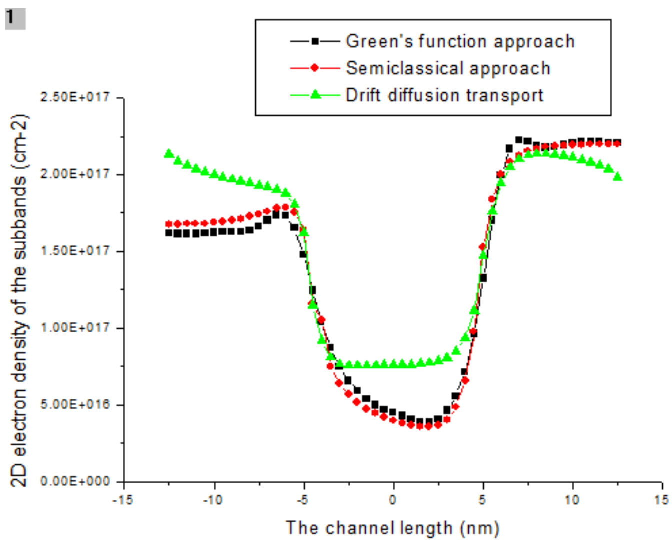

Figure. 5.0: 2D electron density of the sub-bands along channel

4.1.4. SIMULATIONS RESULT AT 4.5nm Tsi

The plot of 2D electron density of subbands along channel at 4.5nm Si film thickness shows that the distribution of electron density of Green's function and semi-classical approach are almost the same for while drift diffusion transport has more electron at channel region

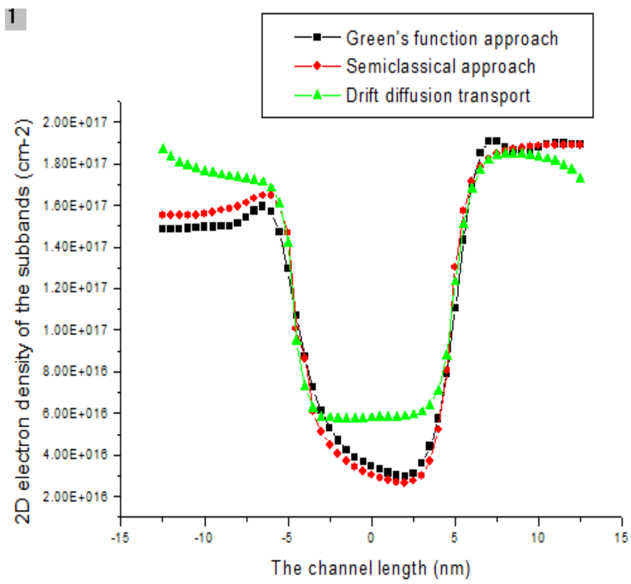

Figure. 6.0: 2D electron density of the sub-bands along channel

4.1.5. SIMULATIONS RESULT AT 5.5nm Tsi

The plot of 2D electron density of sub-bands along channel at Si film thickness of 5.5nm also shows that the distribution of electron density of Green's function and semi-classical approach are almost the same while drift diffusion transport has more electrons at channel region. Generally, the magnitude of 2D electron density of the sub-bands increases as the thickness of Si film increased, since there are more number of electron quantity.

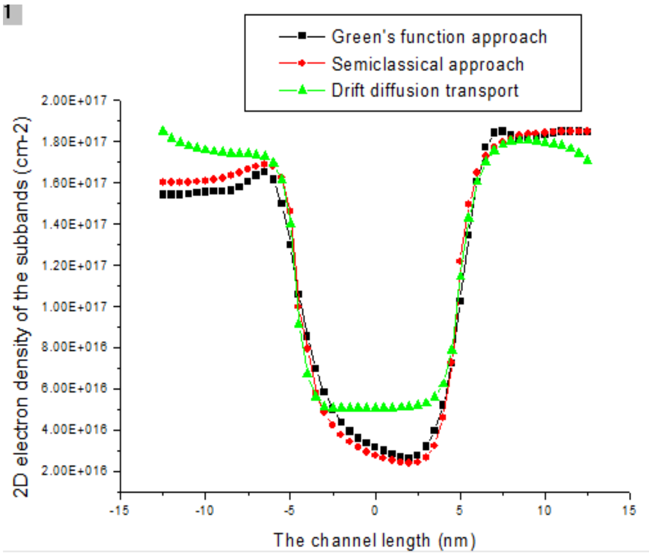

Figure. 7.0: 2D electron density of the sub-bands along channel

4.2. SIMULATIONS RESULT OF SUBBANDS ENERGY PROFILE ALONG CHANNEL

4.2.1. SIMULATIONS RESULT AT 1.5nm Tsi

The plot of sub-bands energy profile along the channel for Si film thickness of 1.5nm shows that Green's function and semi-classical approach have roughly the same potential barrier. On the other hand, drift diffusion transport shows a moderate higher potential barrier.

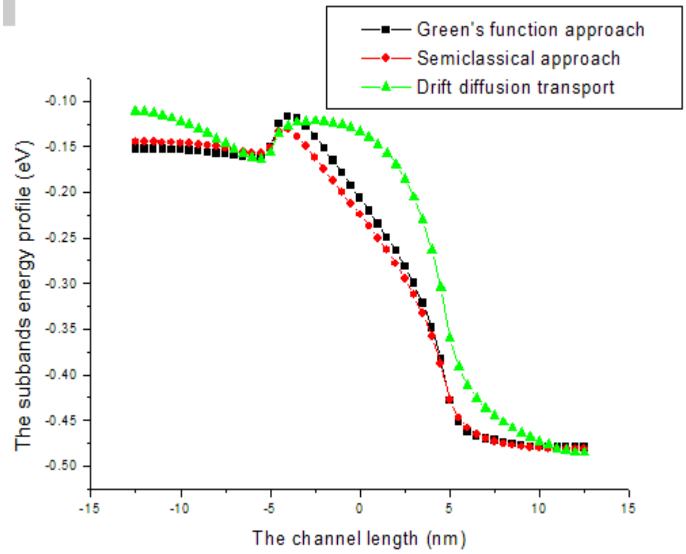

Figure. 8.0: sub-bands energy profile along channel

4.2.2. SIMULATIONS RESULT AT 2.5nm Tsi

The plot of subbands energy profile along the channel for Si film thickness of 2.5nm also shows that Green's function and semi-classical approach have almost the same potential barrier while drift diffusion transport shows a moderate higher potential barrier and is higher than that of 1.5nm

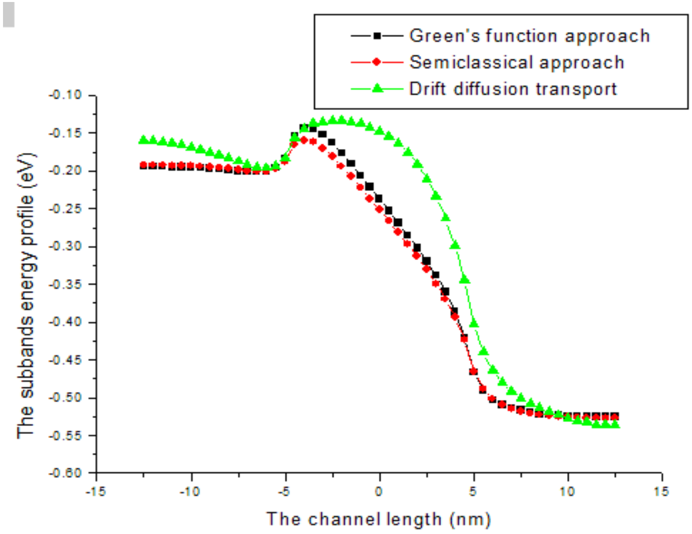

Figure. 9.0: sub-bands energy profile along channel

4.2.3. SIMULATIONS RESULT AT 3.5nm Tsi

The plot at 3.5nm Si film thickness shows that Green's function and semi-classical approach have almost the same potential barrier and is higher than that of 2.5nm. On the other hand, drift diffusion transport shows a moderate higher potential barrier.

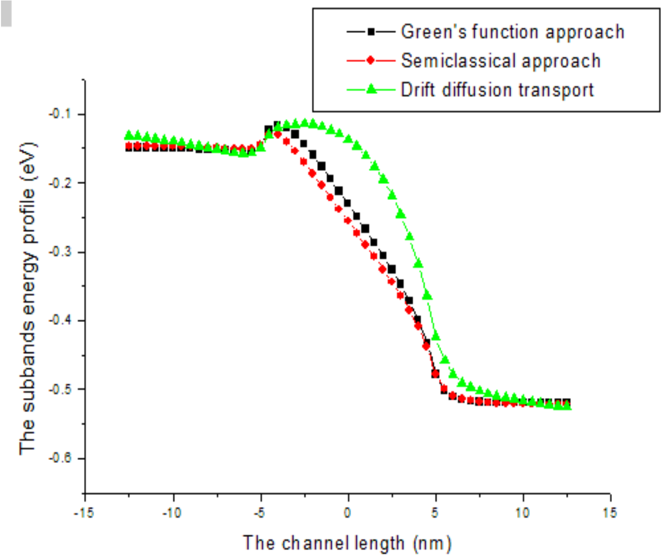

Figure. 10.0: sub-bands energy profile along channel

4.2.4. SIMULATIONS RESULT AT 4.5nm Tsi

The plot at 4.5nm Si film thickness shows that Green's function and semi-classical approach have roughly the same potential barrier and drift diffusion transport shows a moderate higher potential barrier and is more than that of 3.5nm.

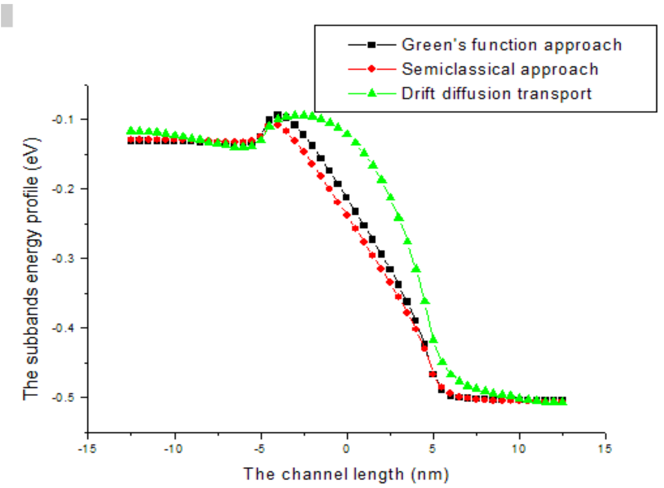

Figure. 11.0: sub-bands energy profile along channel

4.2.5. SIMULATIONS RESULT AT 5.5nm Tsi

The plot at 5.5nm Si film thickness shows that Green's function and semi classical approach have almost the same potential barrier and is higher than that of 4.5nm. On the other hand, drift diffusion transport shows a moderate higher potential barrier and also is higher than that of 4. 5nm.Therefore as thickness of Si film increased, the potential barriers for all 3 transport models increased

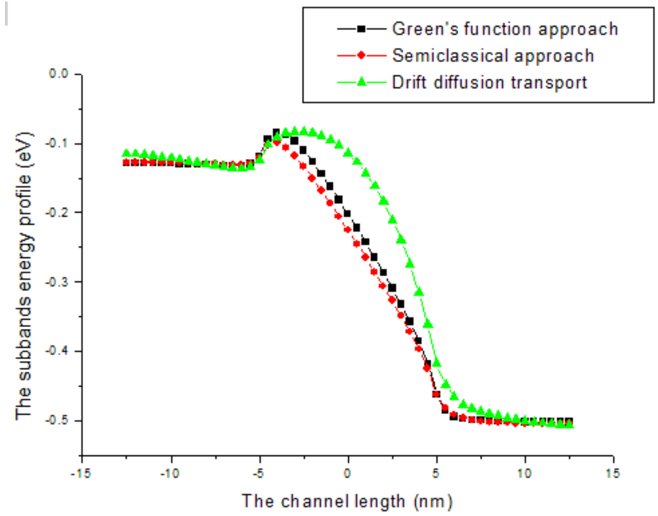

Figure. 12.0: sub-bands energy profile along channel

4.3. SIMULATIONS RESULT OF DRAIN CURRENT AGAINST GATE VOLTAGE

4.3.1. SIMULATIONS RESULT AT 1.5nm Tsi

The plot of drain current versus gate voltage for Si film thickness of 1.5nm shows that Green's function and semi-classical approach have almost the same current at off state as well as on state. On the other hand, drift diffusion transport has the lowest drain current due to scattering mechanism.

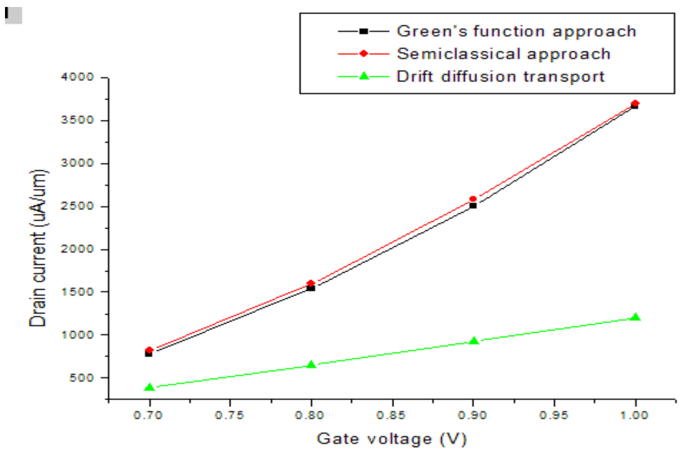

Figure: 13.0: Drain current versus gate voltage

4.3.2. SIMULATIONS RESULT AT 2.5nm Tsi

The plot drain current versus gate voltage for Si film thickness of 2.5nm shows that Green's function and semi-classical approach have almost similar current because are ballistic in nature, while drift diffusion has lowest current due to scattering. However, as thickness of Si film is increased, the peak on state current is also increased for all models.

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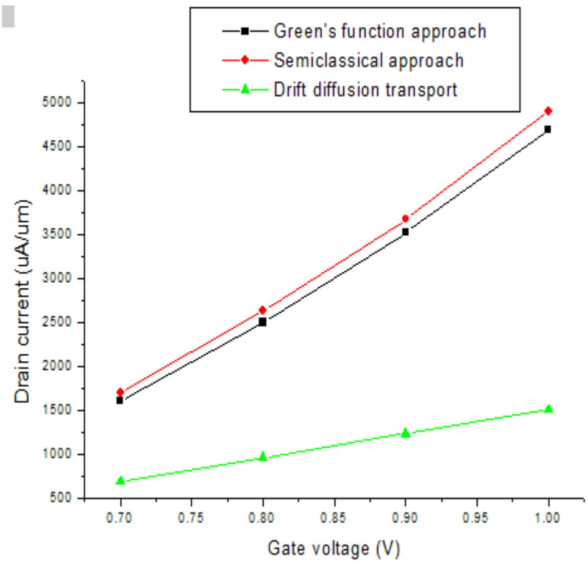

Figure: 14.0: Drain current versus gate voltage

4.3.3. SIMULATIONS RESULT AT 3.5nm Tsi

The plot of drain current versus gate voltage for Si film thickness of 3.5nm shows that Green's function and semi-classical approach have the highest drain current and almost the same, because are ballistic in nature and drift diffusion transport has the lowest drain current because of scattering. However, as thickness of Si film increased, the peak on state current also increased as shown from the plot.

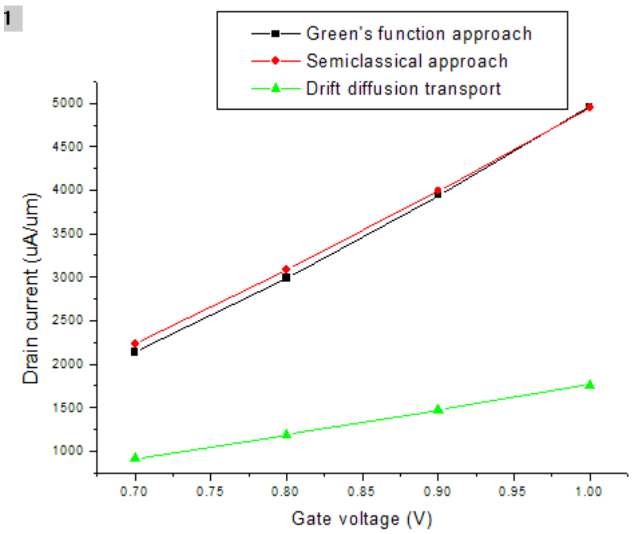

Figure: 15.0: Drain current versus gate voltage

4.3.4. SIMULATIONS RESULT AT 4.5nm Tsi

The plot of drain current versus gate voltage for Si film thickness of 4.5nm shows that Green's function and semi-classical approach have highest drain current and is higher than that of 3.5nm, also drift diffusion transport has lowest drain current and is also higher than that of 3.5nm. Therefore, as thickness of Si film increased, drain current and peak on state current increased.

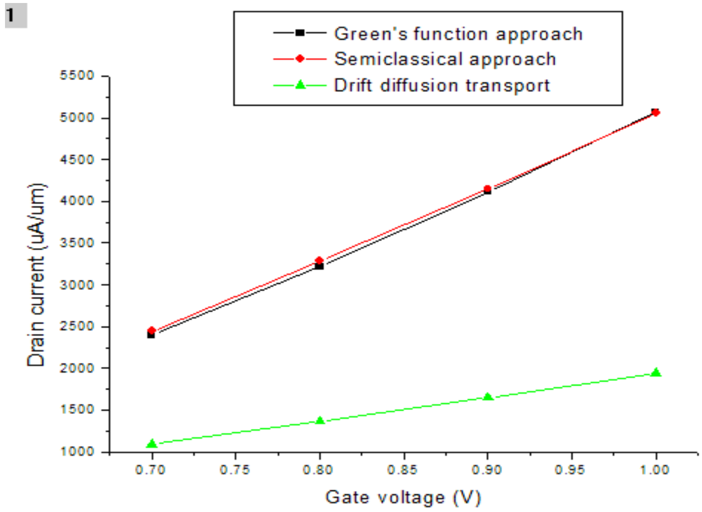

Figure: 16.0: Drain current versus gate voltage

4.3.5. SIMULATIONS RESULT AT 5.5nm Tsi

The plot of drain current versus gate voltage for Si film thickness of 5.5nm shows that Green's function and semi-classical approach have highest drain current compared to 1.5nm, 2.5nm, 3.5nm and 4.5nm. Also, drift diffusion transport has highest drain current compared to 1.5nm, 2.5nm, 3.5nm and 4.5nm. However, the peak on state current is higher than that of 1.5nm, 2.5nm, 3.5nm and 4.5nm.

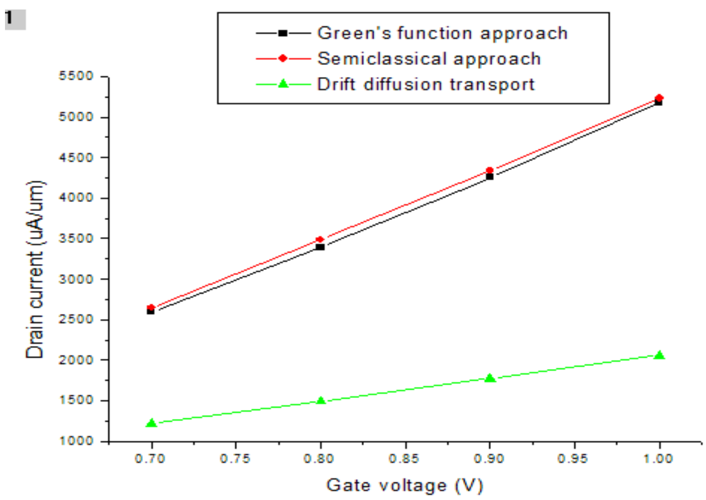

Figure: 17.0: Drain current versus gate voltage

5. CONCLUSION

In this work three transport model studied, from which it was observed that, Green's function and semi-classical approach produced roughly the same characteristics, since both of them deal with ballistic transport. However, drift diffusion transport has the lowest performance due to existence of scattering. When all other structural design of nanomos are fixed, increment in Si film thickness result in more number of electron in the channel region. Thus, it is observed that thick-body nanomos can perform better than thin-body nanomos.

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