A Compact *I-V* Model for FinFETs Comprising Multi-Dimensional Electrostatics and Quantum Mechanical Effects

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Outline

- Introduction
- Methodology Description
- The Charge Model
- Results
- Summary & Conclusions

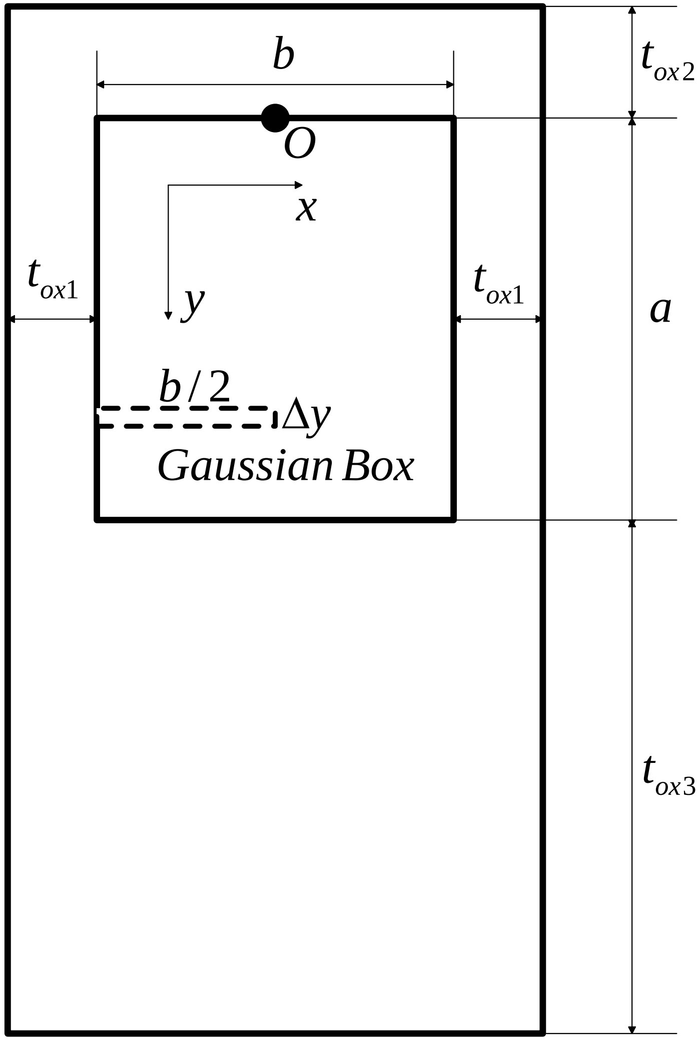
Introduction (I)

- Multi-gate structures have superior device performance, especially the low off-state leakage current.
- Compact models for this type of devices are urgently needed.
- Main challenges: closed-form solution to the coupled Poisson's & Schrödinger equations
- Difficulty under multi-dimensional framework

Introduction (II)

- Previous work mainly deals with 1D analytical modeling for DG-MOSFET or is focused on the 2D electrostatics along transport direction
- This work covers
  - Analytically solving 2D Poisson's & Schrödinger equations for the cross-section of FinFETs
  - Developing compact model for charge, threshold, and current

Methodology Description (I)



- 2D analytical solution to Schrodinger & Poisson's equation
  - 2D trial wavefunctions proposed at the cross-section of the channel as follows:

$$\psi_{i,j}(x,y) = a_{y,j}\sqrt{2/a}\,\sin\left[(j+1)\pi y/a\right]e^{-b_{y,j}y/a} \times$$
$$a_{x,i}/\sqrt{2b}\,\sin\left[(i+1)\pi x/b\right]\left(e^{-b_{x,i}x/b} + e^{-b_{x,i}(b-x)/b}\right)$$

Methodology Description (II)

- Poisson's equation is decomposed into two problems:
  - Poisson's equation with homogeneous BCs

    Green's Function Method
  - Laplace equation with specific BCs

    Separate-of-Variables Method

$$\Phi(x,y) = \underbrace{V_G - \Phi_{MS} + \left[-V_G y / y_2 + aV_G / y_2\right] u(y-a)}_{\text{general solution from Laplace equation}}$$

$$+ \underbrace{\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn} \Psi_{mn}(x,y)}_{\text{particular solution from Poisson's equation}}$$

Methodology Description (III)

- Schrödinger equation is solved by substituting forms for potential and wavefunction. Eigen-energy can be expressed by $b_{x,i}$ and $b_{y,j}$, which are functions of line-charge-density.

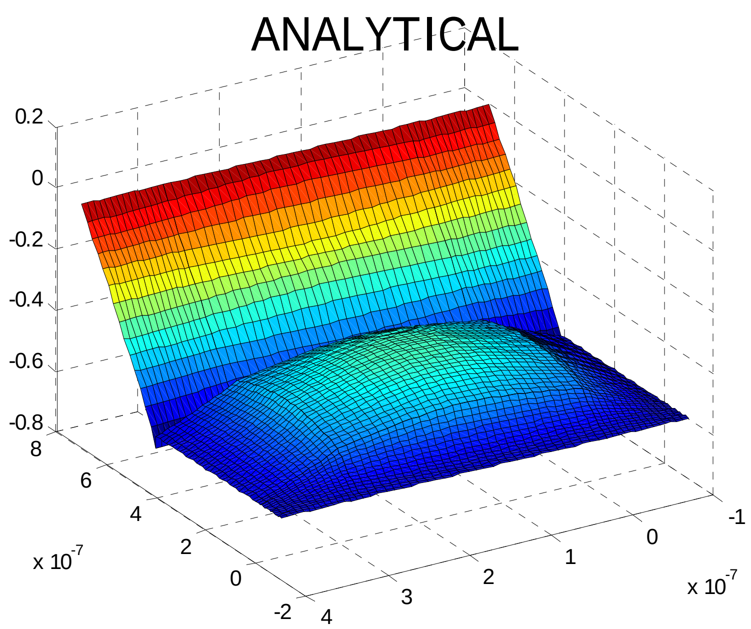
$$\left\langle E_{i,j} \right\rangle = \underbrace{\frac{(i+1)^2 \hbar^2 \pi^2}{2m_x b^2} \left[1 - \frac{b_{x,i}^2}{(i+1)^2 \pi^2} + \frac{b_{x,i} a_{x,i}^2 \left(1 - e^{-2b_{x,i}}\right)}{2\left[b_{x,i}^2 + (i+1)^2 \pi^2\right]} \right]}_{\text{kinetic energy in width direction}} + \underbrace{\frac{(j+1)^2 \hbar^2 \pi^2 a_{y,j}^2 \left(1 - e^{-2b_{y,j}}\right)}{4m_y a^2 b_{y,j}}}_{\text{kinetic energy in height direction}}$$

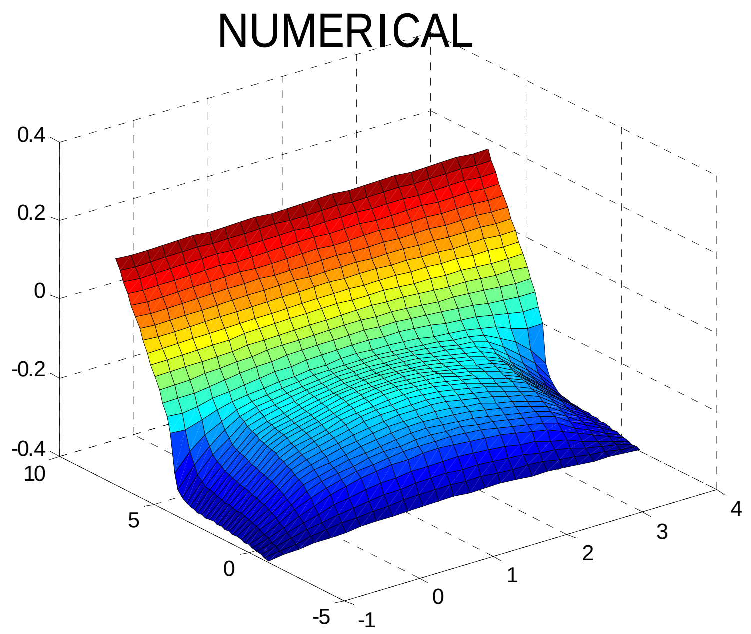
$$\underbrace{-q\left[V_G - \Phi_{MS}\right]}_{\text{potential energy resulted from general solution}} - \underbrace{2q\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn} C_m^i D_n^j / \sqrt{(a+2x_1)(b+y_1+y_2)}}_{\text{potential energy resulted from particular solution}}$$

Methodology Description (IV)

- Derivation of Carrier Line-Density
  - The expression of the carrier line-density as a function of energies is applied, and an implicit form of the line-density is obtained.
  - Introducing the *line effective density-of-states* (LEDOS) to make the implicit form efficient to converge
  - Deducing a closed-form for the line-density
- Application of Ballistic Transport to Establish the Complete *I-V* Model

Potential Comparison





Width equals to 3nm, height equals to 4nm, gate-oxide equals to 1nm and buried oxide equals to 3nm. The gate bias is 0.6V.

Charge Model (I)

- Define LEDOS as the integral of the 1D density of states weighted by the occupation probability in energy space.

$$N_{LEDOS}\left(N_{inv}\right)=\sum_{n_x=1}^{N_x}\sum_{n_y=1}^{N_y}\sum_{k=1}^{N_v}N_k^{'}\sqrt{\pi}\exp\left[-\left(E_{n_x,n_y,k}-E_C\right)/k_BT\right]$$

$$E_C=-q\phi_C,\ \ \phi_C=\Phi\left(b/2,y_{\min}\right)$$

- Therefore, the carrier line density is written as:

$$N_{inv}=N_{LEDOS}\exp\left(q\phi_C/k_BT\right)$$

Charge Model (II)

$$N_{inv} = C_G\left[V_G - \left(\phi_M - \chi\right) - \phi_C - S\left(N_A\right)\right]/q$$

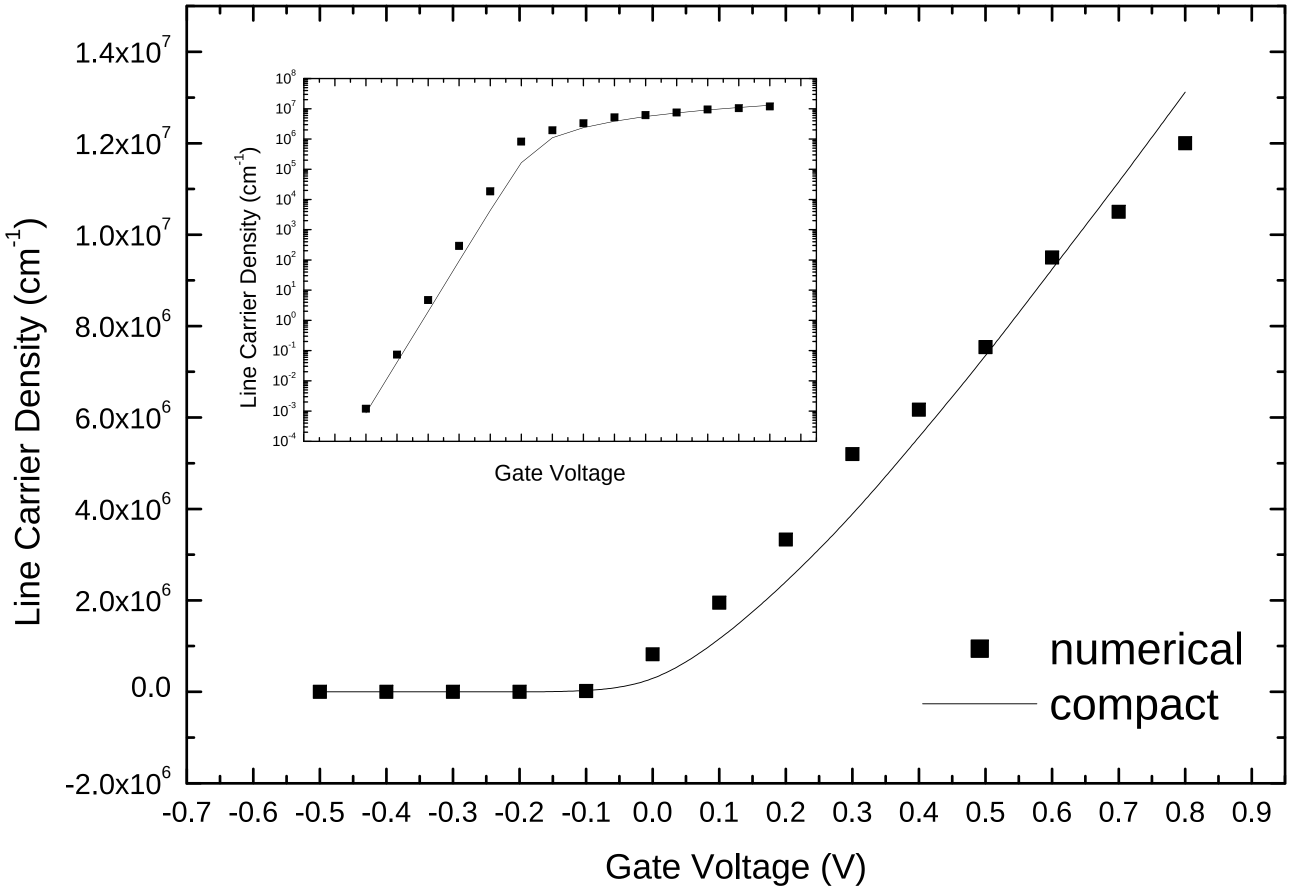
$$S\left(N_A\right) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left\{\frac{2qN_A\sqrt{a_{eff}b_{eff}}}{-\lambda_{mn}mn\pi^2\varepsilon_{si}}\left[\cos\frac{m\pi x_1}{b_{eff}} - \cos\frac{m\pi\left(b + x_1\right)}{b_{eff}}\right]\times\right.$$

$$\left.\left[\cos\frac{n\pi y_1}{a_{eff}} - \cos\frac{n\pi\left(a + y_1\right)}{a_{eff}}\right]\sin\frac{m\pi}{2}\sin\frac{n\pi\left(y_{\min} + y1\right)}{a_{eff}}\right\}$$

$$C_G = 1/\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{4C_m^0 D_n^0}{-\lambda_{mn}\varepsilon_{si}a_{eff}b_{eff}}\sin\frac{m\pi}{2}\sin\frac{n\pi\left(y_{\min} + y_1\right)}{a_{eff}}$$

Charge Comparison

$a = 4\,\text{nm},\ b = 3\,\text{nm},\ t_{ox1} = t_{ox2} = 1\,\text{nm},\ t_{ox3} = 3\,\text{nm},\ N_A = 10^{10}\,\text{cm}^{-3}$

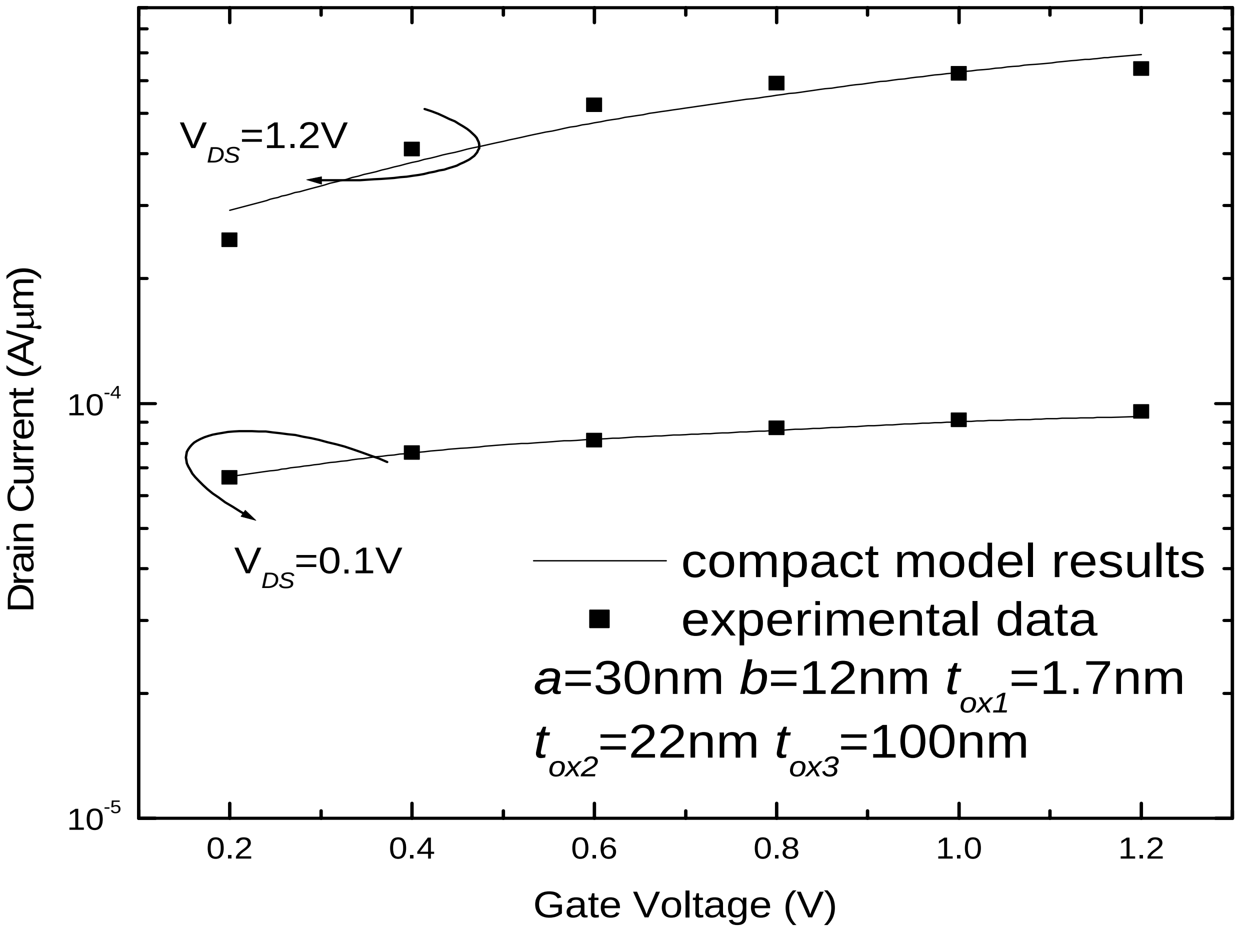


Comparison of the line carrier density between numerical (dots) and compact (lines) results. The logarithmic scale is also shown in the inset.

Current Derivation

- Compact Ballistic *I-V* Model
  - Carriers coming from two ends
  - Using back-scattering coefficient
- Three Differences between FinFET and DG-MOSFET
  - The orders of the Fermi integral are all lowered by ½.
  - The 1D density-of-states is used with units cm^{-1}
  - All the valleys and subbands are considered to make the results more correct since the practical FinFETs are deca-nano scaled and the formula in literature is only applicable for very thin DG-MOSFET.

Comparison of *I-V* Characteristics



Drain current vs. gate voltage under different drain bias.
The experimental data are published by AMD in IEDM 2002.

Summary

- Contributions
  - Derivation of self-consistent analytical solution to 2D Poisson's and Schrödinger equations
  - Concise closed form for charge, threshold, and *I-V* characteristic of FinFETs
  - Fit data well qualitatively

Conclusions

Planned Work

- Parameter extraction strategy
- Potential improvement around the interface between silicon and buried oxide regions
- Combination with charge control MOS model, comparing to threshold voltage based model
- Using the DD transport model, testing the applicability of ballistic transport