Quantum effects in DG FET

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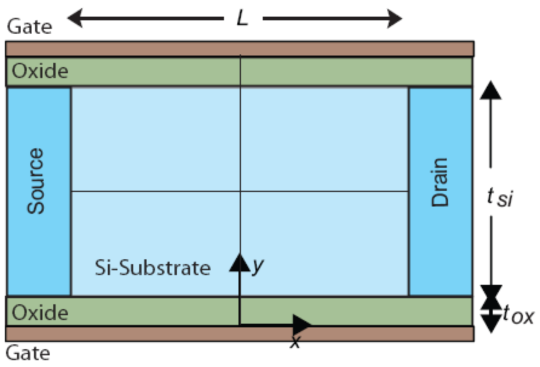
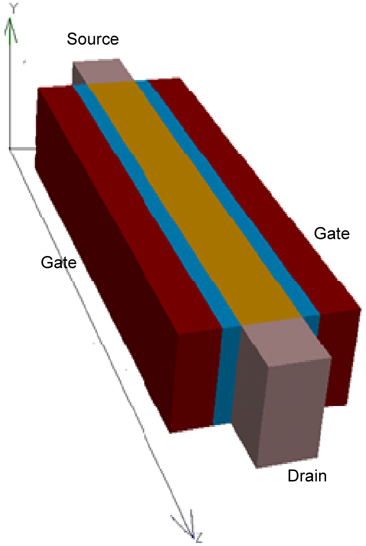
Abstract:

We present a quantum mechanical modeling framework in double-gate (DG) FETs. In case of subthreshold regime, the charge is neglected , thus decoupling quantum effects and electrostatics in the body. For above-threshold regime, we've solved the Poisson's equation with quantum charge density. In case of DG MOSFET, we have solved 1D Schrodinger equation along gate-to-gate axis and for DG FinFET we have solved 2D Schrodinger equation to model the quantum effects.





DG MOSFET specifications:

L = 25 nm, t_{ox} = 1.6 nm, ε_{ox} = 7, N_a = $1\text{x}10^{15}\text{cm}^{-3}$
Near-midgap metal with work function 4.53 eV
Idealized Schottky contacts with work function 4.17 eV
Replace oxide by an electrostatically equivalent insulating Si-layer: $t'_{ox} = t_{ox}\varepsilon_{si}/\varepsilon_{ox}$

DG FinFETspecifications:

L_{Fin}=20nm, H_{Fin}=20nm, T_{Fin}=6nm
Other specifications same as DG MOSFET

Quantum mechanical effects in DG MOSFET (subthreshold)

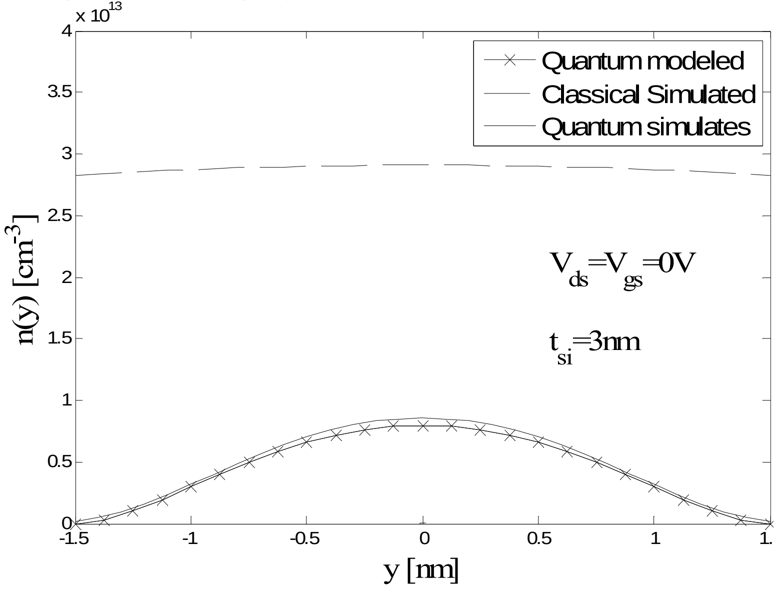
In case of ultra-thin bodies, the structural confinement outruns the electronic confinement. The confined electrons are perturbed by parabolic potential variation along gate-to-gate axis. To accurately model the quantum effects, the Schrödinger equation along the gate-to-gate axis is solved to evaluate the eigenfunctions (which correspond to harmonic oscillator in a box [1]) in terms of *parabolic cylindrical functions* and the corresponding eigenvalues. [2]

As in the case of UTBs, only lower subbands are important, the polynomials are truncated to evaluate compact eigenfunctions and eigenvalues.

First subband eigenfunction and eigenvalue:

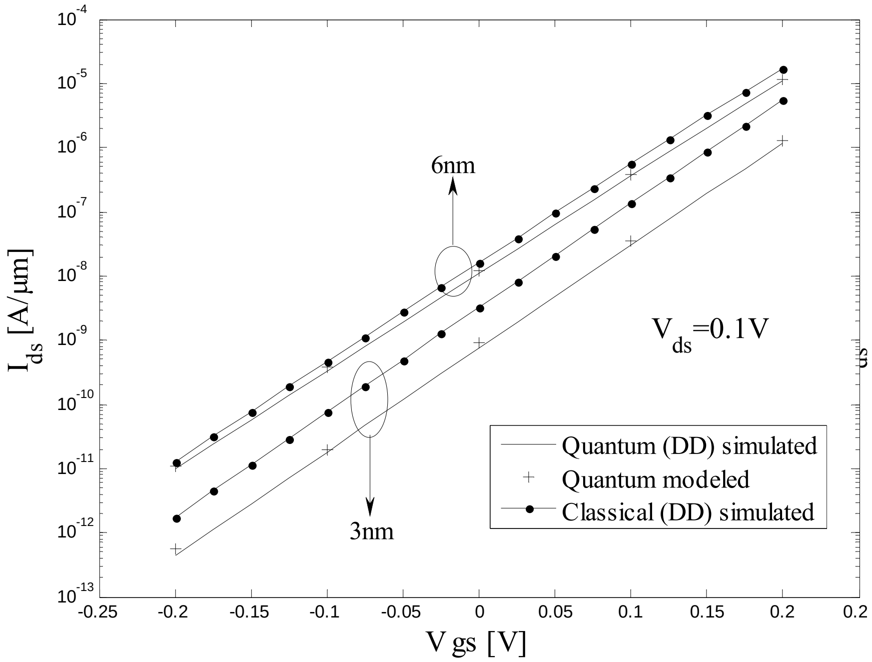
$$\psi_1(y) = \sqrt{\frac{15}{8t_{si}}}\left(1 - \frac{4y^2}{t_{si}^{\ 2}}\right)$$

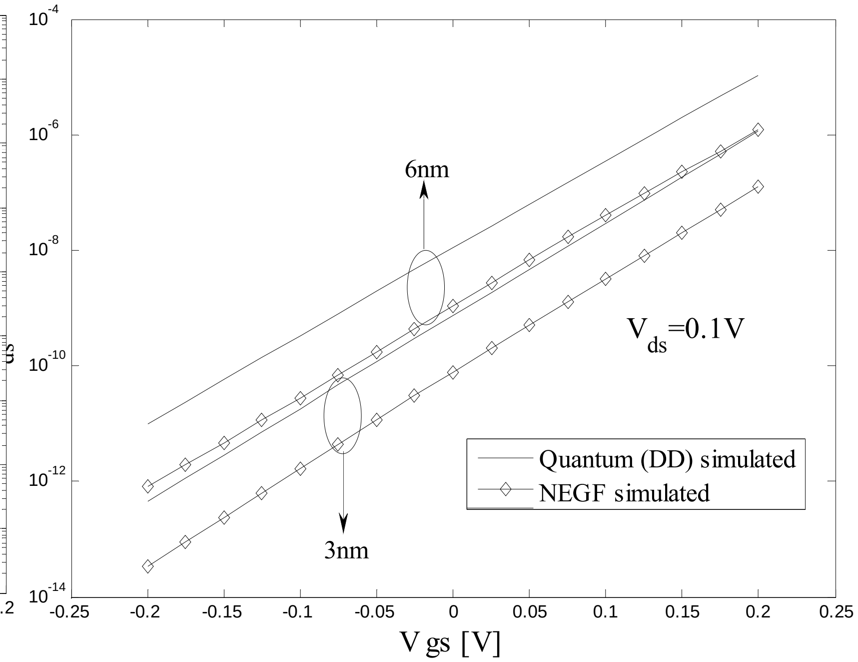
$$E_1 = \frac{4\hbar^2}{m_l^{\ *} t_{si}^{\ 2}}$$



Comparison of modeled and numerically simulated electron density along y-axis for 3nm device at V_{gs}=V_{ds}=0 V.

Quantum drain current modeling





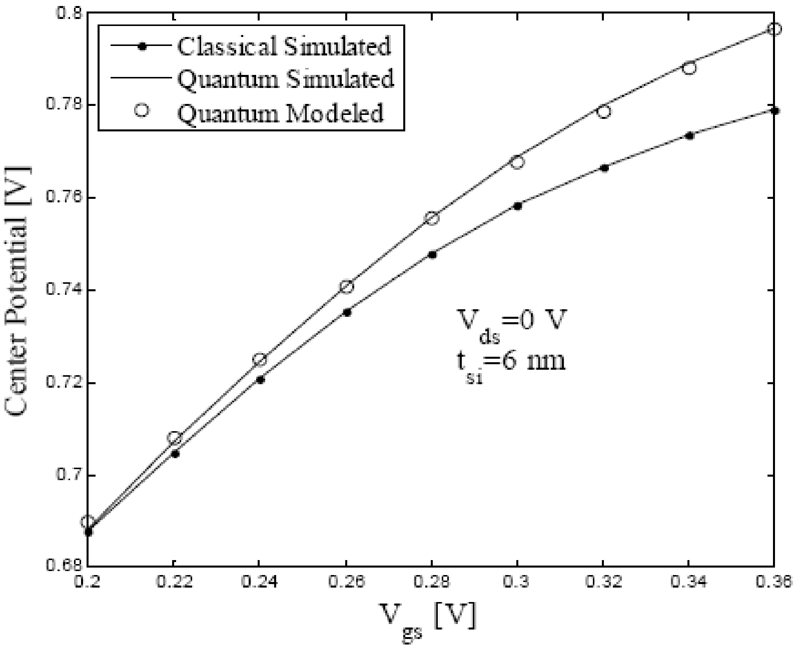
Comparison of modeled (symbols) and numerically simulated (solid curves) subthreshold I_{ds}-V_{gs} characteristics for different silicon thicknesses at V_{ds}=0.1 V.

$$I_d = \frac{Wq\mu_n V_{th}\left[1-\exp\left(-\frac{V_{ds}}{V_{th}}\right)\right]\sum_{valleys}\sum_{j}\frac{kTm_{Di}^{*}}{\pi\hbar^2}e^{-\frac{(E_j+E_g/2+q(\varphi_b-\varphi_i))}{kT}}}{\int_{-L/2}^{L/2} e^{-\frac{q\varphi(x,0)}{kT}}\,dx}$$

Comparison of numerically simulated subthreshold I_{ds}-V_{gs} characteristics using different transport formalisms for different silicon thicknesses at V_{ds}=0.1 V. The lower current in case of Non-equilibrium green function (NEGF) simulations is attributed to higher mobility used for DD simulations

Quantum mechanical effects in DG MOSFET (above-threshold)

- Poisson equation is solved using quantum charge density along gate-to-gate axis to evaluate the quantum potential
- As quantum charge-density is lower than the classical charge density, classical methodology underestimates the total potential.
- Increasing difference between classical potential and quantum potential in above-threshold regime actually reduces the quantum effects in ultra-thin bodies.



$$\frac{d^2\varphi_Q(y)}{dy^2} = \frac{q\sum_{valleys}\sum_{j}\frac{kTm_{Di}^{*}}{\pi\hbar^2}\ln\left(1+e^{\frac{(E_F-E_j)}{kT}}\right)\left|\psi_j(y)\right|^2}{\varepsilon_s}$$

$$-\varphi_Q(0)e^{-\frac{q\varphi_Q(0)}{kT}} = \frac{15qN_o}{8t_{si}\varepsilon_s}\left(\frac{11t_{si}^{2}}{120}+\frac{4t_{si}t'_{ox}}{15}\right)$$

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2D Quantum mechanical effects in DG FinFET

To determine the quantum effects in DG FinFET, we need to solve the 2D Schrodinger equation given as :

$$-\frac{\hbar^2}{2}\left[\frac{1}{m_x^*}\frac{\partial^2\psi(x,y)}{\partial x^2}+\frac{1}{m_y^*}\frac{\partial^2\psi(x,y)}{\partial y^2}\right]+bx^2\psi(x,y)=E_{x,y}\psi(x,y)$$

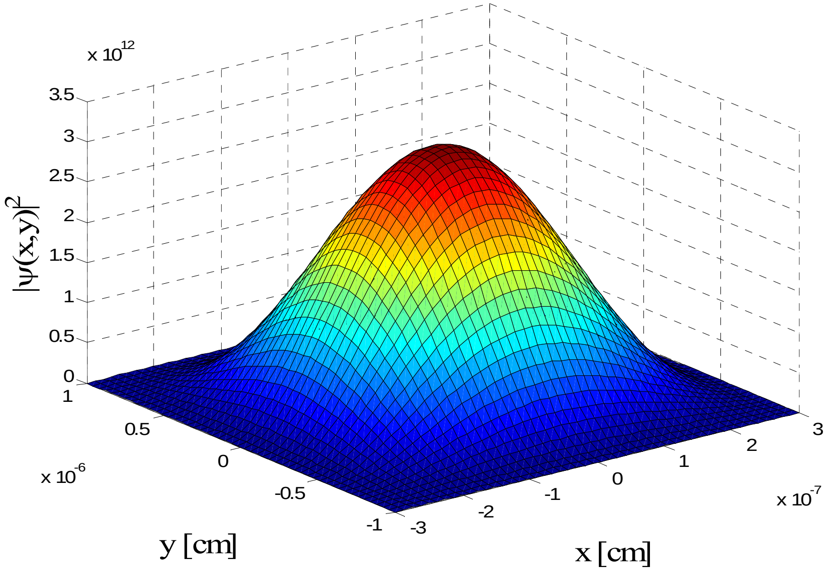
To solve the above equation, we split the complete Hamiltonian into two different independent Hamiltonians for different coordinate x and y. The independent equations are then solved separately for each valley (longitudinal and transverse).
As the potential is nearly constant along the height of the body (*y*-axis), equation in *x* corresponds to the equation for harmonic oscillator in a box (described before) and equation in *y* corresponds to the equation for particle in a box. The potential can be obtained from the DG conformal mapping solution

First subband eigenfunction and eigenvalue:

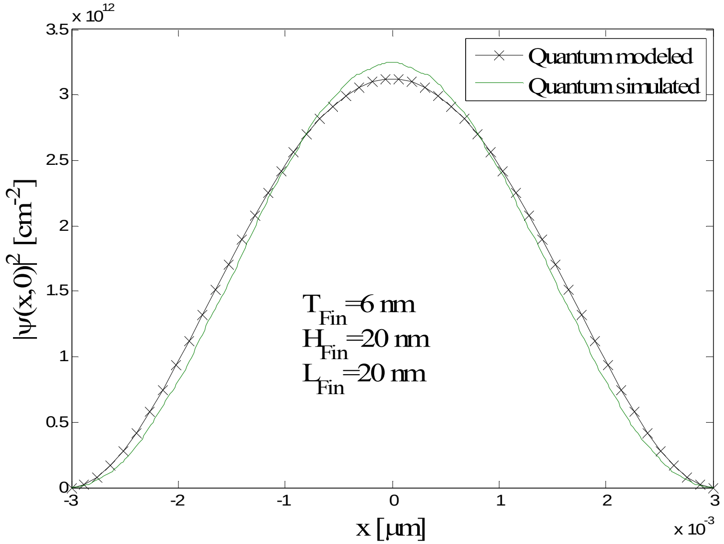
$$\psi_1(x,y)=\sqrt{\frac{15}{4T_{Fin}H_{Fin}}}\left(1-\frac{4x^2}{T_{Fin}{}^2}\right)\sin\left(\frac{\pi(y+H_{Fin}/2)}{H_{Fin}}\right)$$

$$E_1=\frac{4\hbar^2}{m_l^*T_{Fin}{}^2}+\frac{\hbar^2\pi^2}{2m_t^*H_{Fin}{}^2}$$

2D Quantum mechanical effects in DG FinFET (results)



2D probability density function (eigenfunction squared) for the first subband .



Cutline of the probability density function at the device center, compared with numerical simulations..

Conclusions

We have developed a precise quantum modeling framework for short-channel nanoscale DG FETs in subthreshold and near-threshold regime. The eigenfunctions are obtained as a direct solution of Schrodinger equation. It's been shown that in case of ultra-thin body devices the classical potential is lower than quantum potential. The modeled current show good agreement with simulated results.

References

1. A. Consortini and B. R. Frieden, Italian Physical Society, vol. 35, no. 2, 1976
2. Udit Monga and T. A. Fjeldly, "*Compact Quantum Modeling Framework for Nanoscale Double-Gate MOSFET*," Proc. NSTI-Nanotech 2009, accepted.