Compact Quantum Modeling Framework for Nanoscale Double-Gate MOSFET

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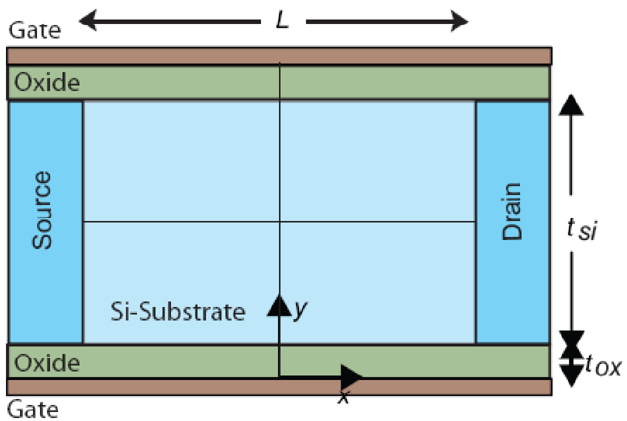
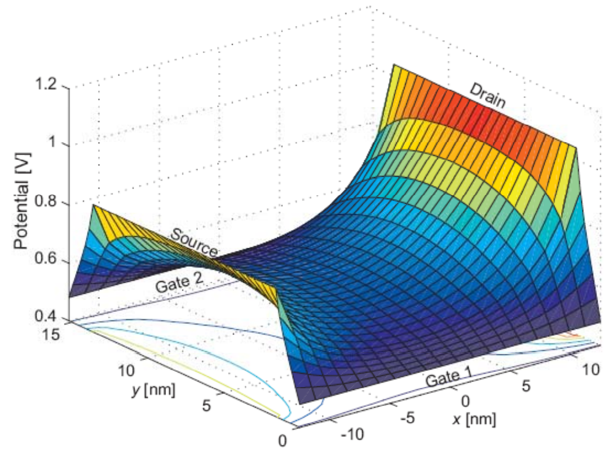
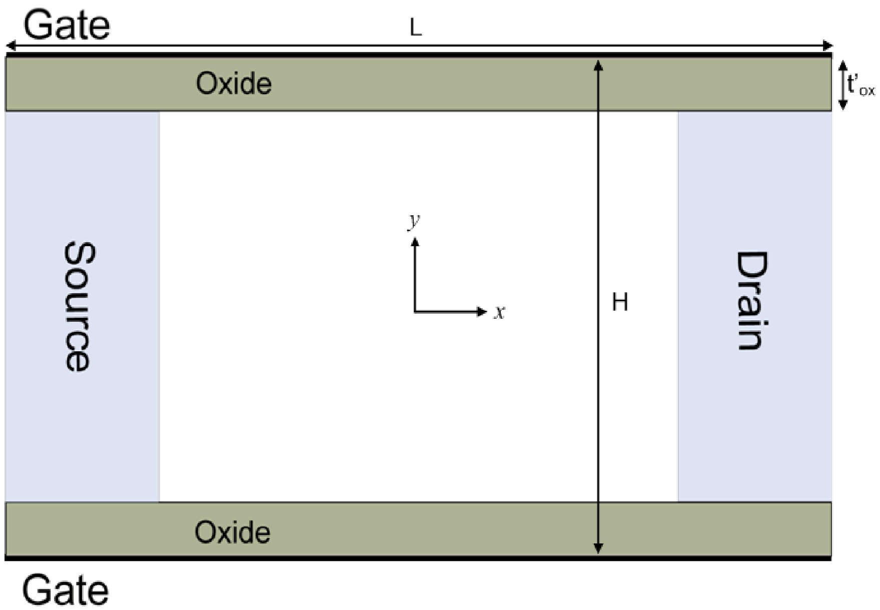




Outline

- *Conformal mapping of DG (Double-gate) MOSFETs*
- *Subthreshold potential modeling*
- *Quantum mechanical modeling*
- *Quasi-Fermi potential modeling in the subthreshold*
- *Potential modeling in the near-threshold regime*
- *Current modeling*
- *Conclusion*

DG device layout



Device specifications:

L = 25 nm, t_{ox} = 1.6 nm, ε_{ox} = 7, N_a = 1x10^{15}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: $t'_{ox} = t_{ox}\varepsilon_{si}/\varepsilon_{ox}$

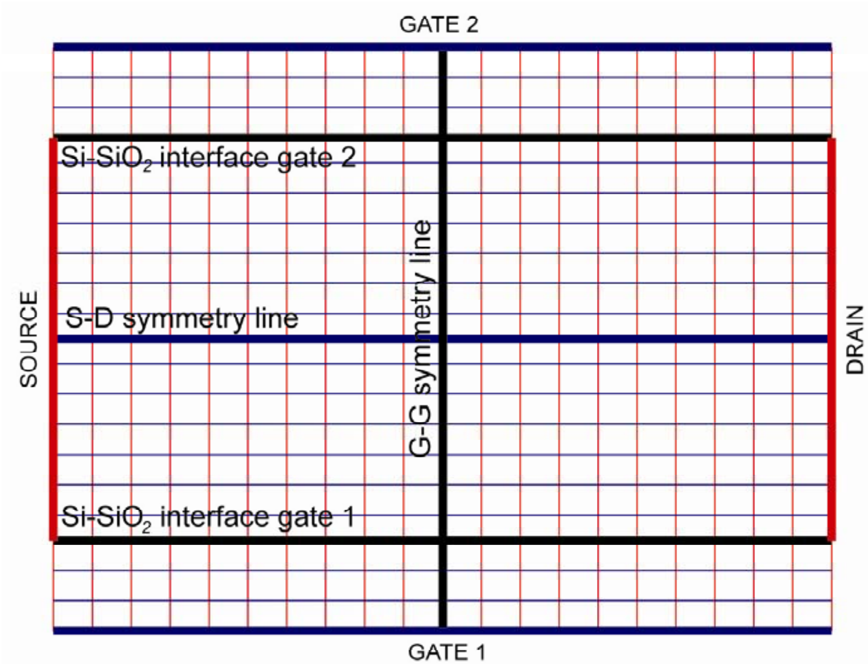
Conformal mapping of DG MOSFET

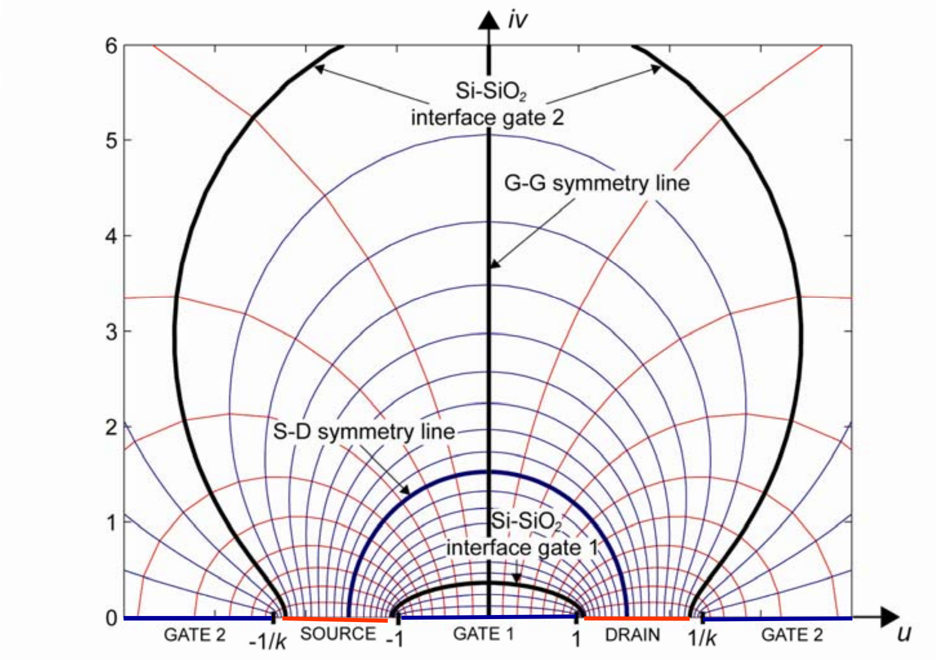
Schwartz-Christoffel transformation

$$z = x + iy = \frac{L}{2}\frac{F(k, u+iv)}{K(k)}$$

$$F(k,w) = \int_0^w \frac{dw'}{\sqrt{(1-w'^2)(1-k^2 w'^2)}}, \quad K(k) = F(k,1)$$

Modulus *k* determinded by *L*/*H*



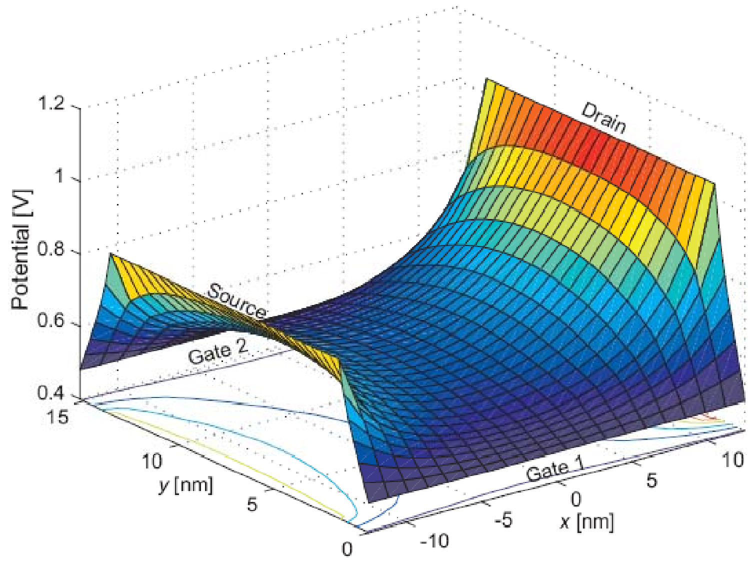


Subthreshold potential modeling

- Solve *Laplace's equation* in (u,iv)-plane
- Obtain *analytical solution* for 2-D inter-electrode potential distribution
- Map back to (x,y)-plane
- Apply to subthreshold

Potential distribution (thin oxide approx):

$$\varphi(u,v)=\frac{v}{\pi}\int_{-\infty}^{\infty}\frac{\varphi(u')}{(u'-u)^2+v^2}du'=\frac{1}{\pi}\left\{\begin{array}{l}(V_{GS2}-V_{FB})\left[\pi-\tan^{-1}\left(\frac{1-ku}{kv}\right)-\tan^{-1}\left(\frac{1+ku}{kv}\right)\right]\\+(V_{GS1}-V_{FB})\left[\tan^{-1}\left(\frac{1-u}{v}\right)+\tan^{-1}\left(\frac{1+u}{v}\right)\right]\\+V_{bi}\left[\tan^{-1}\left(\frac{1-ku}{kv}\right)-\tan^{-1}\left(\frac{1-u}{v}\right)\right]\\+(V_{bi}+V_{DS})\left[\tan^{-1}\left(\frac{1+ku}{kv}\right)-\tan^{-1}\left(\frac{1+u}{v}\right)\right]\end{array}\right\}$$



Potential distribution
V_{GS} = V_{DS} = 0.2 V

Quantum mechanical modeling

- In case of ultra-thin bodies (UTBs) the effect of structural confinement dominates 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
- The resulting eigenfunctions are in terms of parabolic cylindrical functions (even and odd infinite polynomials)
- For lower subbands, the polynomials are truncated to give compact solutions of the eigenfunctions and corresponding eigenvalues

$$-\frac{\hbar^2}{2m_y^*}\frac{d^2\psi(y)}{dy^2}+\left[q\varphi_c(x)\left(\frac{2y}{H}\right)^2\right]\psi(y)=E\psi(y)$$

Eigenfunction and the eigenvalue corresponding to the first subband of the longitudinal valley:

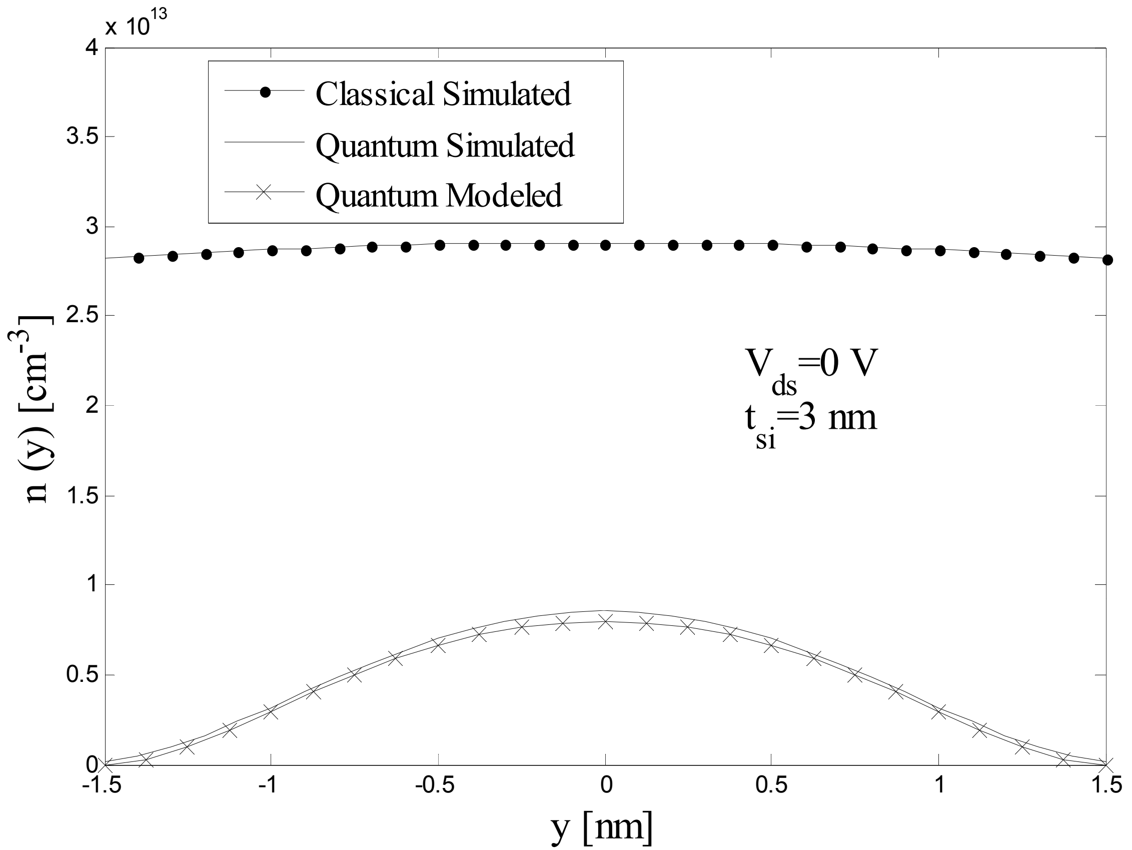
$$\psi_1(y)=\sqrt{\frac{15}{8t_{si}}}\left(1-\frac{4y^2}{t_{si}^{\ 2}}\right)$$

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

Corresponding electron density along y-axis is given as:

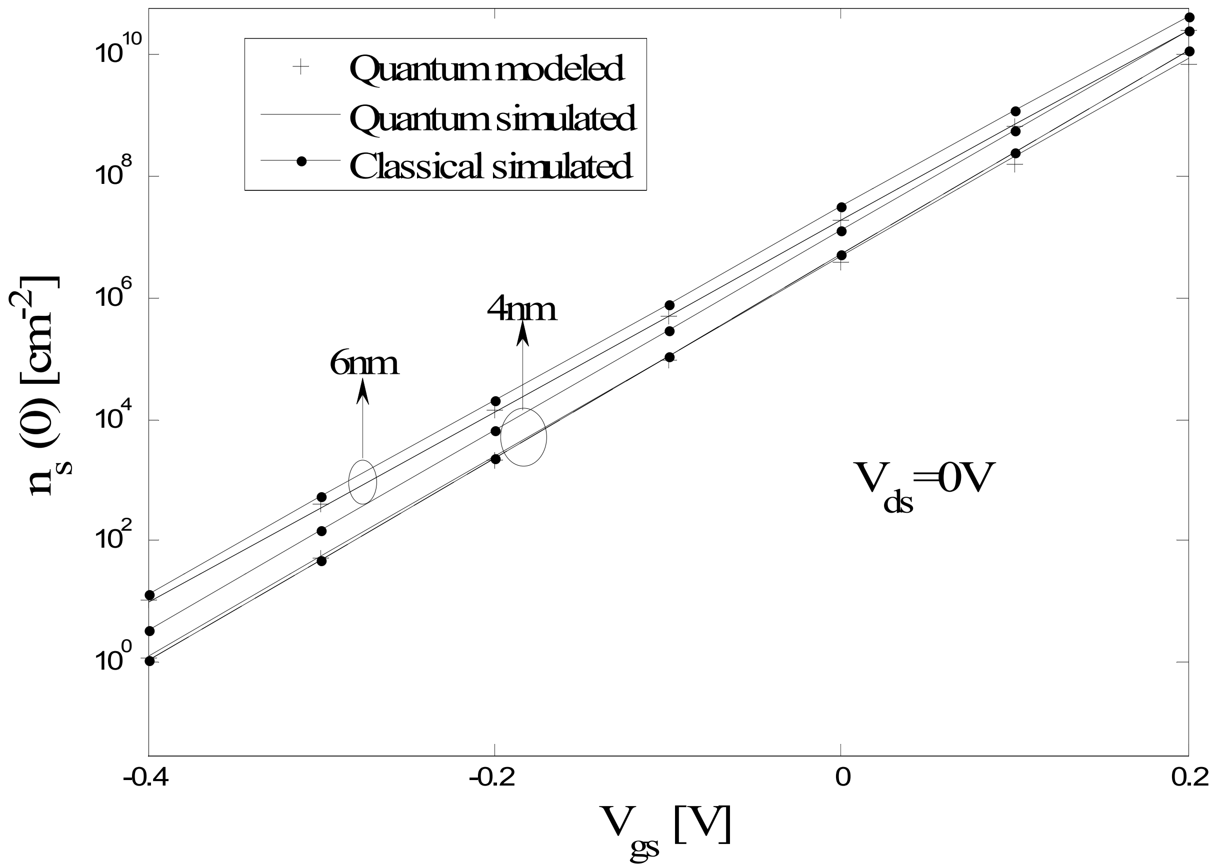
$$n_s(y)=\sum_{valleys}\sum_j g_v N_{2D}\ln\left(1+\exp\left[-\frac{(E_j(x)-E_F)}{kT}\right]\right)|\psi(y)|^2$$

Quantum mechanical modeling (Results)



V_{gs} =0 V

Quantum mechanical modeling (Results)



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Quasi-Fermi potential modeling in the subthreshold regime

Differential form of drift-diffusion equation is solved to obtain following expression of the quasi-Fermi level:

$$V_F(x) = C_1 - V_{th}\ln\left[\frac{C_2}{k_s L} - \frac{\sqrt{2\pi}}{V_{th}} Erf\left(\frac{2x}{k_s L}\right)\right]$$

C_1 and C_2 are obtained from boundary conditions, parameter k_s depends upon V_{ds}, a value of k_s=0.26 (for V_{ds}≤0.25V) and 0.19 (for V_{ds}≥0.25 V) gives sufficient accuracy. The above expression is evaluated for two different regions $x \le x_m$ and $x \ge x_m$

x_m is the position of the top of the barrier, given as:

$$x_m = \frac{L}{2}\frac{F(k, u_m)}{K(k)}$$

u_m is the position of top of the barrier in (u,v) space.

To completely evaluate the quasi-Fermi level expression, we also need the value of Fermi level at the top of the barrier (V_{Fm}), given as:

$$V_{Fm} = -V_{th}\ln\left[1 - \frac{1-\exp\left(-\frac{V_{ds}}{V_{th}}\right)}{\int_{-L/2}^{L/2}\frac{dx}{n_{so}(x)}}\int_{-L/2}^{x_m}\frac{dx}{n_{so}(x)}\right] \approx V_{th}\ln\left(\frac{2}{1+\exp\left(-\frac{V_{ds}}{V_{th}}\right)}\right)$$

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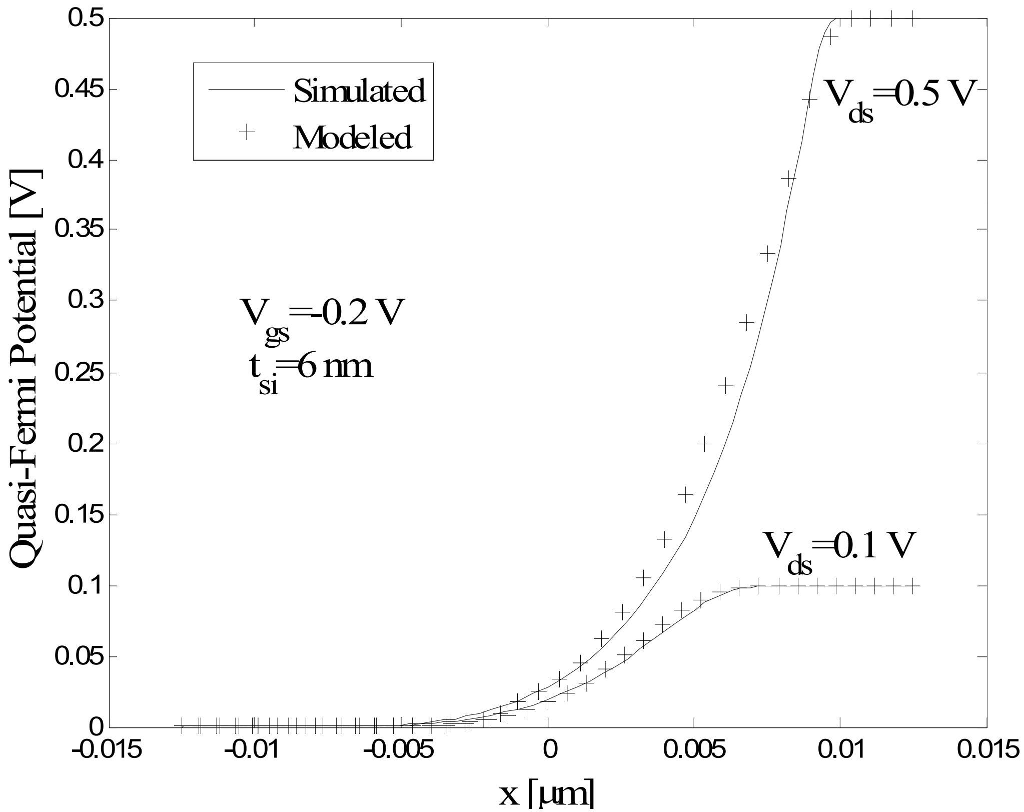
Quasi-Fermi potential (results)



Near-threshold regime

As we move to the near threshold, the effect of charge carriers becomes more important and can't be neglected. The total potential inside the device body is given as:

$$\varphi(x,y) \approx \varphi_L(x,y) + \varphi_Q(x,y)$$

$\varphi_L(x,y)$: Inter-electrode potential

$\varphi_Q(x,y)$: Charge potential

For characteristic length < *L*/2 (present case), the lateral electric field due to charge carriers is negligible near the device center for reasonable drain voltages

Thus charge potential near the center can be evaluated by solving 1-D Poisson's equation

Classical treatment of charge carriers results in underestimation of the total potential, and thus to model accurate potential we solve Poisson's equation with charge density calculated quantum mechanically.

Few assumptions…

- We assume that only first subband is occupied.

- *Although this assumption is quite justified for UTBs, it generates some error for relativity higher thicknesses.*
- *The error can be corrected after solving the Poisson's equation, and replacing one subband charge density with total charge density including all subbands.*

- We assume a non-degenerate carrier statistics near the threshold voltage

- *At the onset of threshold, the charge density is still low and thus the non-degenerate statistics gives negligible error.*

Quantum Potential Model

Poisson's equation with quantum mechanical charge density at the device center:

$$\frac{d^2\varphi_Q(y)}{dy^2} = \begin{cases} 0 & -\left(t'_{ox} + t_{si}/2\right) \le y \le -t_{si}/2 \\ \dfrac{15qkTm_l^*}{4\pi\hbar^2 t_{si}\varepsilon_s} \exp\left[-\dfrac{(E_j - E_F)}{kT}\right]\left(1 - \dfrac{4y^2}{t_{si}^2}\right)^2 & -t_{si}/2 \le y \le t_{si}/2 \end{cases}$$

Total potential at the device center:

$$\varphi_c \approx \varphi_L(1/\sqrt{k}) - \frac{15qN_o}{8t_{si}\varepsilon_s}\left(\frac{11t_{si}^2}{120} + \frac{4t_{si}t'_{ox}}{15}\right)$$

$$N_o = \frac{2kTm_l^*}{\pi\hbar^2}\exp\left(-\frac{\left[E_j + E_g/2 + q\left\{\varphi_b - \varphi_i - \varphi_Q(0) - \varphi_L(1/\sqrt{k})\right\}\right]}{kT}\right)$$ *:For single subband*

$$N_o = \left(\sum_{valleys}\sum_j g_v N_{2D}\exp\left[-\frac{(E_j + E_g/2 + q\varphi_b - q\varphi_i - \varphi_L - \varphi_Q)}{kT}\right]\right)$$ *:With single subband correction*

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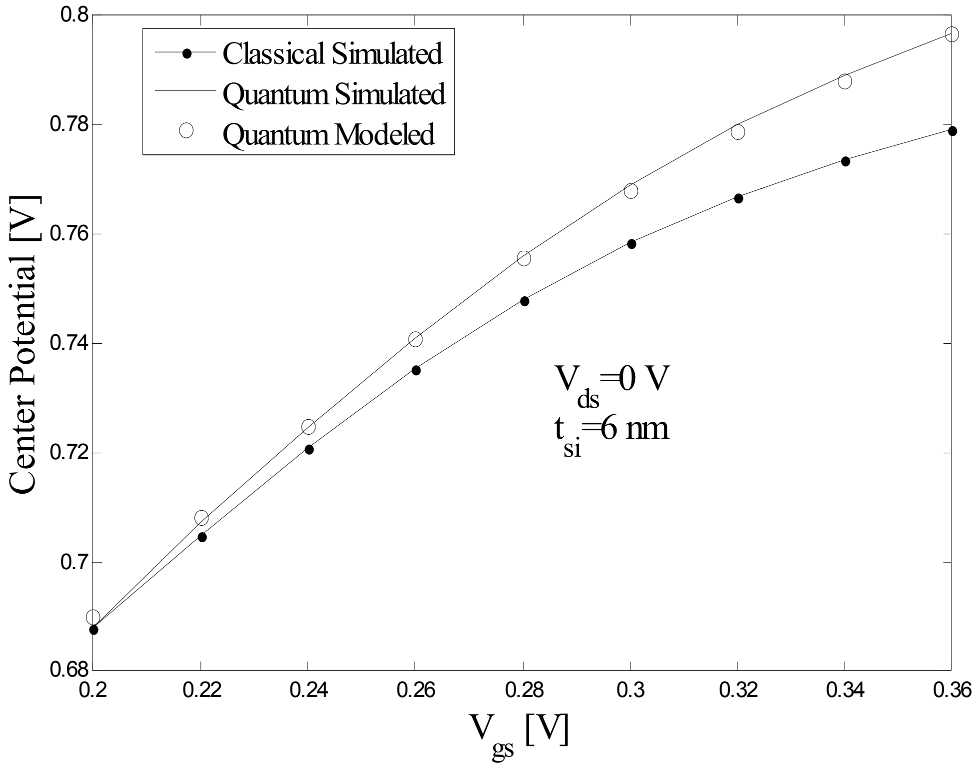
Comparison with numerical simulations



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Subthreshold current modeling

Drain current based on drift-diffusion theory can be expressed as:

$$I_d = \frac{Wq\mu_n kT\left[1-\exp\left(-\frac{V_{ds}}{V_{th}}\right)\right]}{\int_{-L/2}^{L/2}\frac{dx}{n_{so}(x)}}$$

$n_{so}(x)$ is charge-sheet density along the channel direction. Again using non-degenerate carrier statistics $n_{so}(x)$ can be approximated as:

$$n_{so}(x) = \sum_{valleys}\sum_{j} g_v N_{2D} exp\left(-\frac{\left[E_j + E_g/2 + q\{\varphi_b - \varphi_i - \varphi(x,0)\}\right]}{kT}\right)$$

φ_b is the potential difference between the Fermi level of intrinsic silicon and doped silicon.

φ_i represents shift in intrinsic Fermi level from difference in electron and hole density states

$\varphi(x,0)$ is potential along the S-D symmetry line. The potential can be approximated by parabolic function given as:

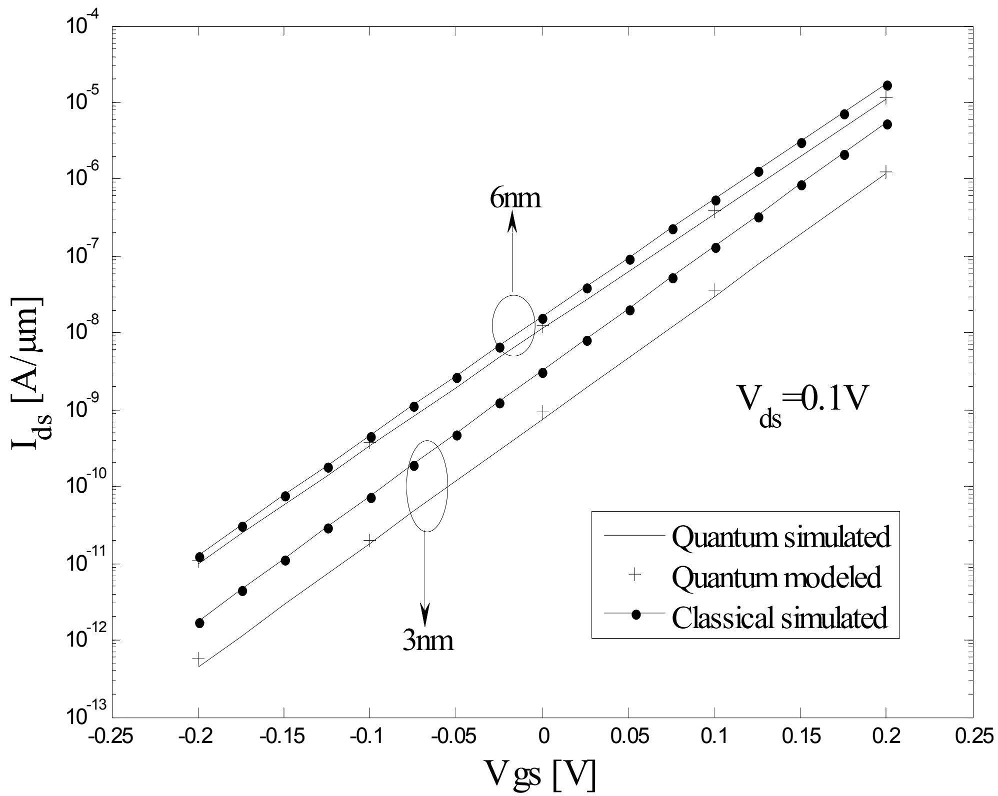
$$\varphi(x,0) \approx \varphi_m + (\varphi_{s/d} - \varphi_m)\left(\frac{x_m - x}{x_m \pm \frac{L}{2}}\right)^2$$

$\varphi_{s/d}$:Potential at source/drain

φ_m :Potential at top of the barrier

x_m :Position of the top of the barrier

Current modeling results



Conclusions

- A precise quantum modeling framework for short-channel nanoscale DG MOSFETs in subthreshold and near-threshold regime is developed

- 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

- Model verified by numerical simulations (ATLAS).