Compact Modeling for Double Gate and Surround Gate MOSFETs

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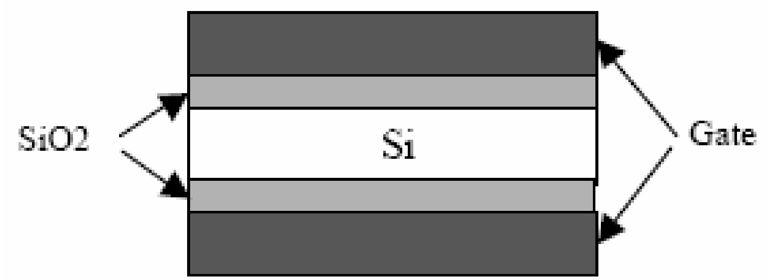
Topics

- Double and surround gate MOSFETs.
- Poisson equation at strong inversion.
- Boundary conditions.
- Analytical solutions based on Lambert function.
- Iterative method.
- Channel current models of the Double Gate (DG).
- Quantum effect correction for the DG current.
- Results and comparisons of the double gate.
- Corrections to the printed version of the paper

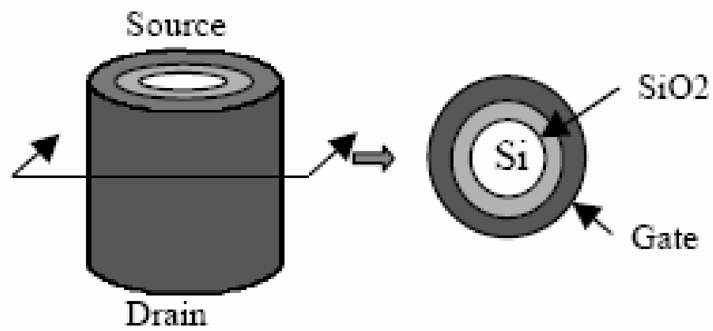
Double and surround gate

- Double gate



(a)

- Surround gate



(b)

Poisson equation at strong inversion

- Double gate

$$\frac{d^2V}{dx_1^2} = \frac{q}{\varepsilon_{si}} n_i e^{q(V-\phi)/kT}$$

- Surround gate

$$\frac{1}{r_1}\frac{d}{dr_1}\left(r_1\frac{dV}{dr_1}\right) = \frac{q}{\varepsilon_{si}} n_i e^{q(V-\phi)/kT}$$

Scaling:

$$(w,\varphi) = q(V,\phi)/kT$$

$$x = x_1/L_d$$

$$r = r_1/L_d$$

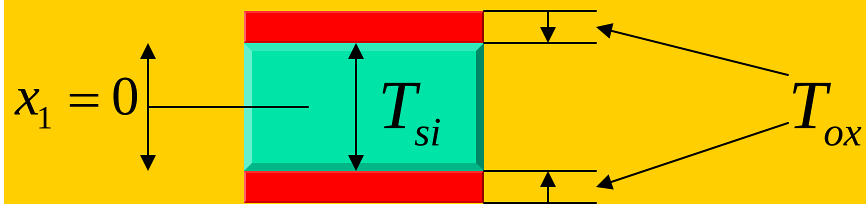
$$L_d = \sqrt{\frac{kT\varepsilon_{si}}{2n_i q^2}}$$

$$2\frac{d^2w}{dx^2} = e^{(w-\varphi)}$$

$$\frac{2}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right) = e^{(w-\varphi)}$$

Boundary conditions

- **Double gate**

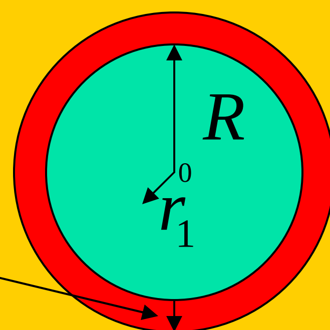


$$C_{ox}(V_{gs} - V_{fb} - V_s) = \pm\varepsilon_{si} \left.\frac{dV}{dx_1}\right|_{x_1 = \pm T_{si}/2}$$

$$V(0) = V_s$$

$$C_{ox} = \varepsilon_{ox} / T_{ox}$$

- **Surround gate**



$$C_{ox}(V_{gs} - V_{fb} - V_s) = \varepsilon_{si} \left.\frac{dV}{dr_1}\right|_{r_1 = R}$$

$$V(R) = V_s$$

$$C_{ox} = \frac{\varepsilon_{ox}}{R \ln\left(\frac{R + T_{ox}}{R}\right)}$$

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Analytical solutions based on Lambert function

- **Double gate**

$$v_{gs} - \varphi = 2\ln(c_1\theta\sec(\theta)) + c_2\theta\tan(\theta)$$

$$\theta = \Phi^{-1}\left(\frac{2}{c_2}\,\mathrm{LambertW}\left(\frac{c_2}{2c_1}e^{(v_{gs}-\varphi)/2}\sin(\theta)\right)\right)$$

$$\theta = \frac{1}{4}e^{\omega_m/2}t_{si},\ c_1 = 4\frac{L_D}{T_{si}},\ c_2 = 4\frac{\varepsilon_{si}}{\varepsilon_{ox}}\frac{T_{ox}}{T_{si}}$$

$$w_m = w(0) - \varphi$$

$$\Phi^{-1}(z) = \varsigma - (\varsigma\tan(\varsigma) - z)/(\tan(\varsigma) + \varsigma\sec^2(\varsigma))$$

$$\varsigma = \sqrt{\frac{z\gamma + 1 - \sqrt{(z\gamma - 1)^2 - 4z(z\delta - 1/3)}}{2(z\delta + \gamma - 1/3)}}$$

$$\gamma = \frac{40}{9\pi^2},\ \delta = \frac{16}{9\pi^4}$$

- **Surround gate**

$$v_{gs} - \varphi = \ln\left(k_1\frac{(1-\beta)}{\beta^2}\right) + k_2\frac{1-\beta}{\beta}$$

$$\beta = \frac{1}{1 + \frac{2}{k_2}\mathrm{LambertW}\left(\frac{1}{2}\sqrt{1-\beta}\frac{k_2}{\sqrt{k_1}}e^{\frac{1}{2}(v_{gs}-\varphi)}\right)}$$

$$k_1 = 16\frac{L_D^2}{R^2},\ k_2 = 4\frac{\varepsilon_{si}}{\varepsilon_{ox}}\ln\left(1 + \frac{T_{ox}}{R}\right),\ \beta = 1 - b\frac{R^2}{L_D^2}$$

$$b = \frac{1}{16}e^{(w(0)-\varphi)}$$

- **LambertW is a solution to** $W(x)e^{W(x)} = x$

Iterative Method

- **Double gate**

$$\theta_{n+1} = \Phi^{-1}\left(\frac{2}{c_2} LambertW\left(\frac{c_2}{2c_1} e^{(v_{gs}-\varphi)/2} \sin(\theta_n)\right)\right)$$

$$\theta_0 = \frac{c_1}{c_2+1} e^{-(v_{gs}-\varphi)/2}\left(\sqrt{1+\frac{2(c_2+1)}{c_1^2} e^{(v_{gs}-\varphi)}} - 1\right)$$

- **Surround gate**

$$\beta_{n+1} = \frac{1}{1+\frac{2}{k_2}\mathrm{LambertW}\left(\frac{1}{2}\sqrt{1-\beta_n}\frac{k_2}{\sqrt{k_1}} e^{\frac{1}{2}(v_{gs}-\varphi)}\right)}$$

$$\beta_0 = 0$$

Channel Current

- **Double Gate (DG)**

$$I_{ds} = \mu_n kT \frac{W}{L} \int_{\phi_s}^{\phi_d} \left(\int_0^{T_{si}} n dx_1 \right) d\phi$$

$$I_{ds} = 16 V_{th}^2 \frac{\mu_n \varepsilon_{si}}{T_{si}} \frac{W}{L} \left[ids(\theta) \right]_{\theta_d}^{\theta_s}$$

$V_{th} = kT / q$ and

$$ids(\theta) = \theta \tan(\theta) - \frac{1}{2}\theta^2 + \frac{1}{4} c_2 \theta^2 \tan^2(\theta)$$

Quantum effect correction for the DG current.

- **Double Gate**

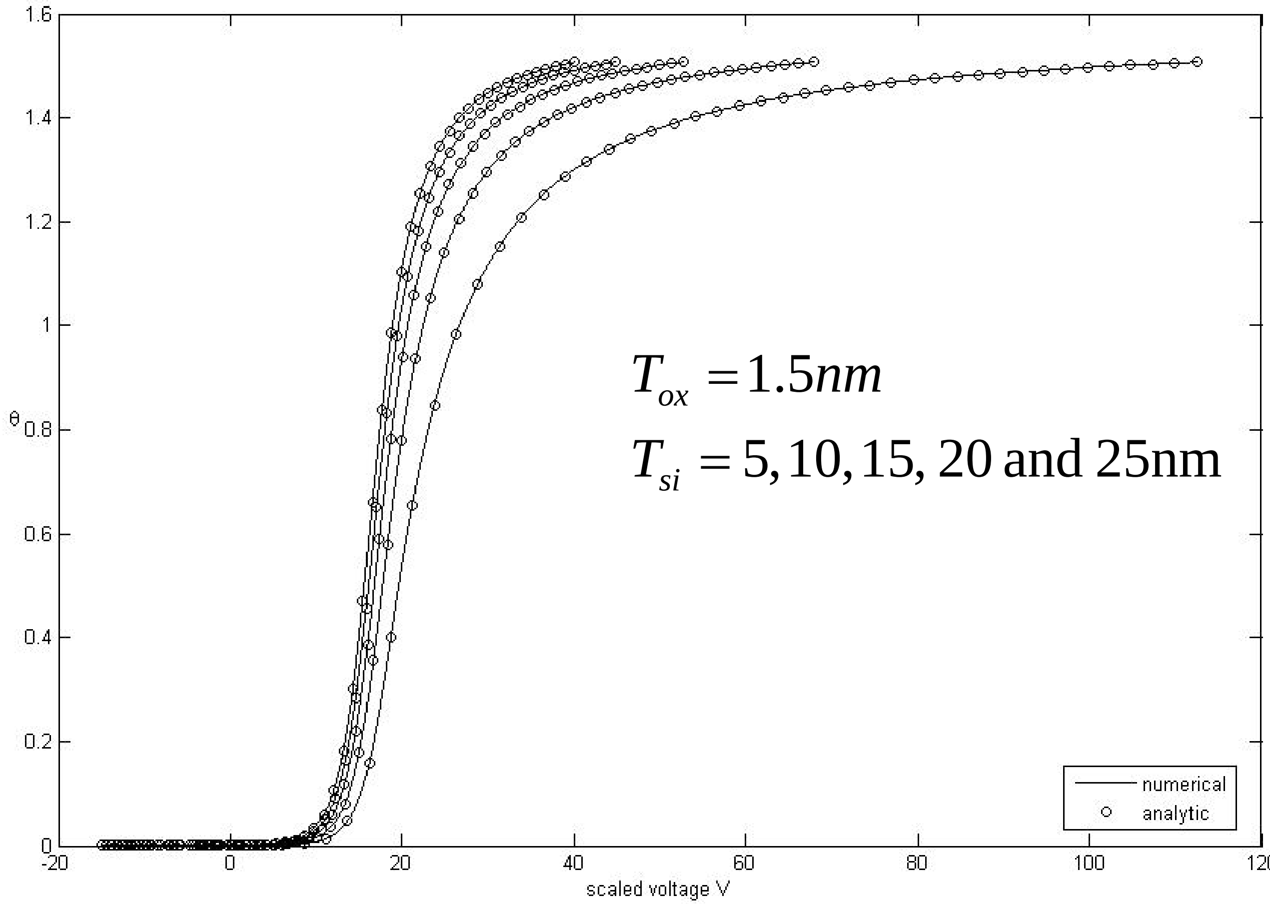
$$I_{DS,quantum} = I_q \left[idsQ(\theta) \right]_{\theta_D}^{\theta_S}$$

$$idsQ(\theta) = \int \theta^2 \sec^2(\theta) \frac{d\varphi}{d\theta} d\theta$$

$$I_q = \varepsilon \mu_n V_{Th}^2 \frac{\varepsilon_{si}}{L_D} \frac{W}{L} \frac{16\sqrt{2}R_1}{t_{si}^2}$$

$$\varepsilon = \frac{\hbar}{2L_D\sqrt{rm^* qV_{th}}}$$

$$\frac{d\varphi}{d\theta} = \frac{2}{\theta} + 2\tan(\theta) + c_2 \frac{d}{d\theta}(\theta \tan(\theta))$$



A comparison of the exact numerical and iterative solutions (each 5 iterations).

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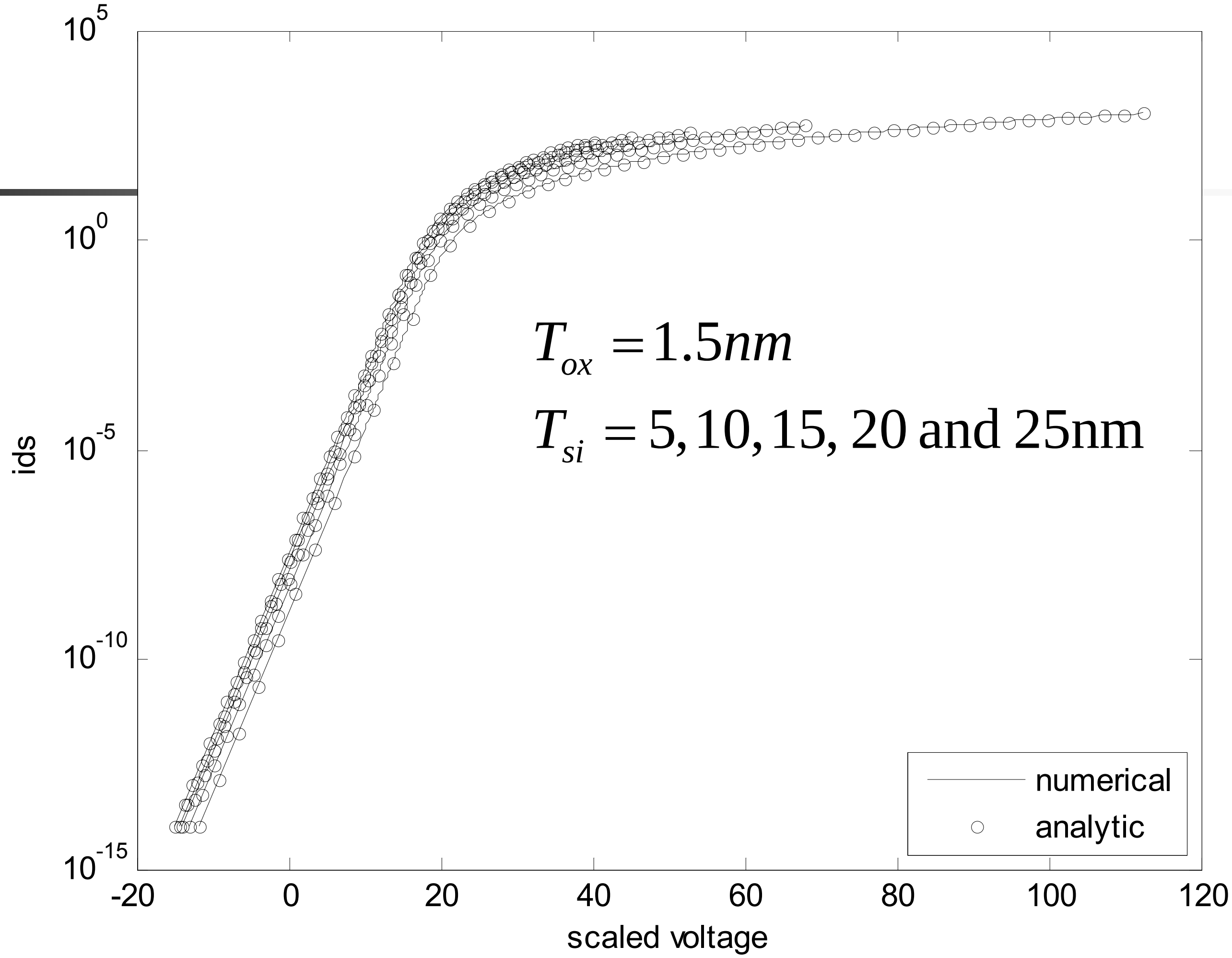
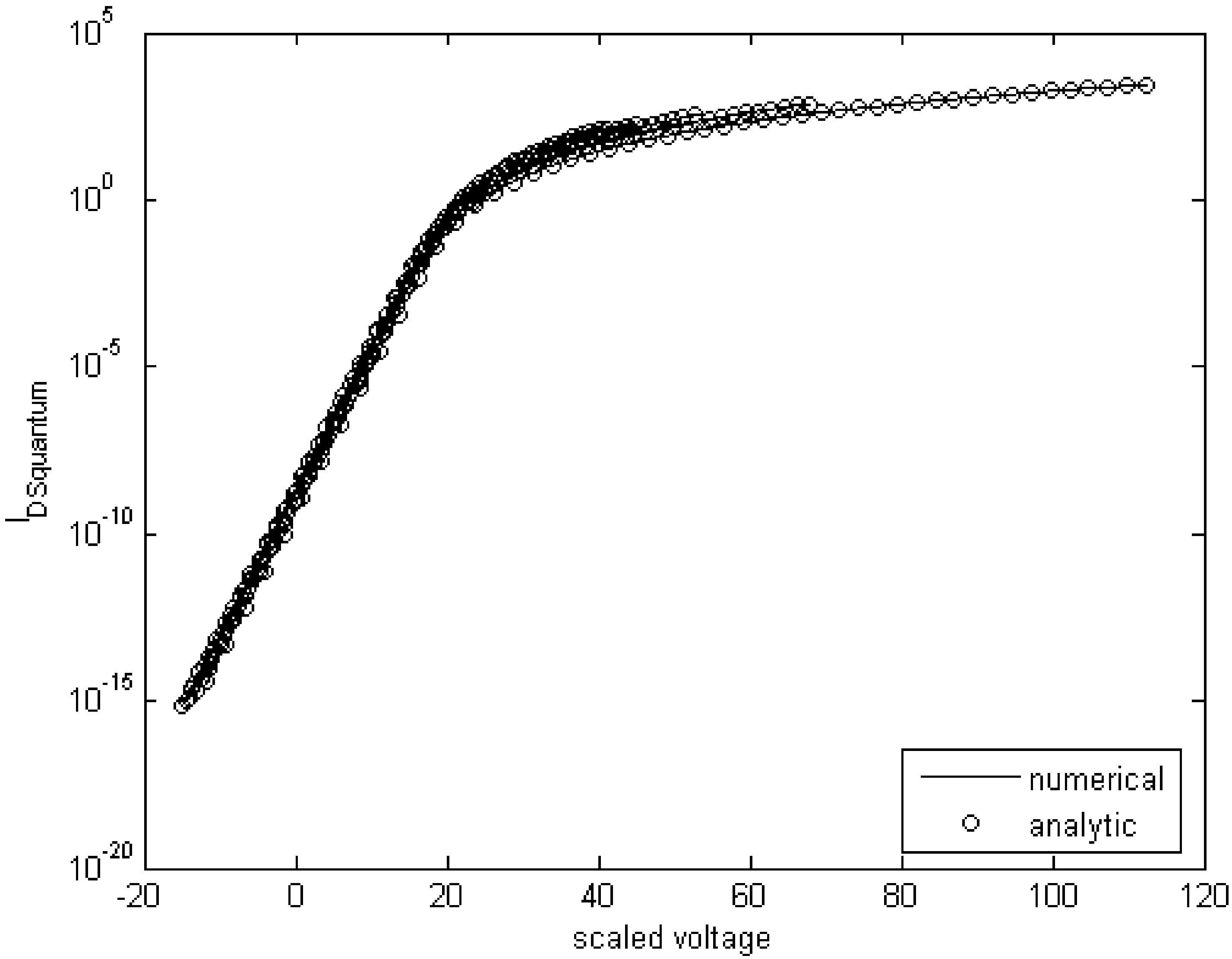


A comparison of the exact numerical and iterative solutions for the scaled current ids(θ) (each 5 iterations).



A comparison of the exact and analytic solutions for a scaled quantum current correction

Corrections to the printed version of the paper

- In equation (5) and (15): The thermal voltage V_{th} should be squared
- c_1 should be replaced by c_2 in equation (5).
- Above Figure 2, "(?)", in the text the various cases are $T_{si} = 5, 10, 15, 20 \text{ and } 25\text{nm}$
- In Figure 3 the current is a scaled current ids(θ).
- In equation (15) the coefficient of the current should be divided by the channel length L.
- The quantum effect section of the paper is incomplete.