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Workshop on Compact Modeling

An Improved Analytical Solution to the Surface Potential in Un-doped Surrounding-Gate MOSFET

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Overview of the talk

- Surrounding-Gate MOSFET: An Introduction
- Previous Modeling Approaches
- Present Modeling Strategy
- Results Obtained from the Present Analytical Model
- Conclusions

Surrounding-Gate MOSFET: An Introduction

Schematic of a Surrounding-Gate MOSFET

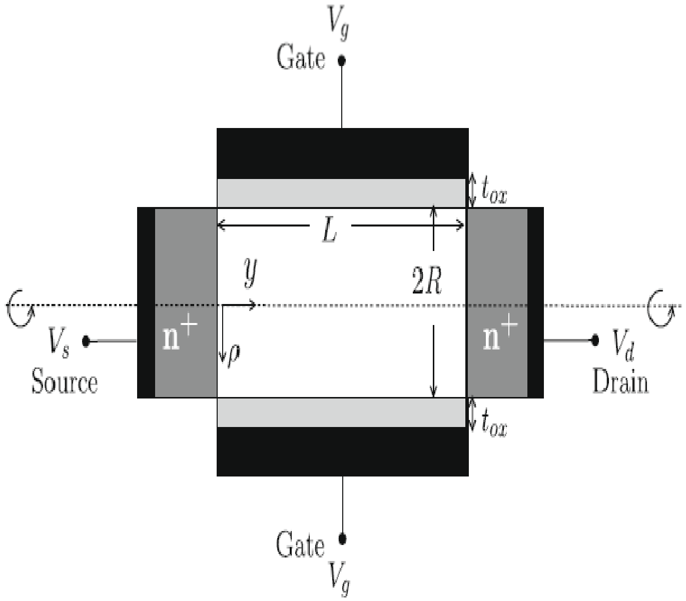

Fig. 1 SRG MOS

[1] J.P.Colinge, *Solid State Electron*, 2004, pp:897–905.

Advantages of Surrounding-Gate structures

- Presence of ultra thin body and ultra thin gate oxide increases transverse electric field, resulting in reduced SCE. This reduction is the maximum in Surrounding-Gate MOS [1]. Ultra-thin body also results in mobility reduction. For Surrounding-Gate MOSFET the need for very thin body is minimum [1].

- An un-doped body results in higher mobility due to less impurity scattering and also reduces random dopant fluctuations.

- Presence of semi-insulating back oxide reduces parasitic capacitances and leakage greatly

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General Modeling Strategy

- Solve the Poisson equation in one dimension, under Gradual Channel Approximation.
- Express the potential along radial direction in terms of some implicit state variables and/or the potential at the center.
- Equate the normal electric field at the Si-SiO_2 interface to form an implicit equation of the state variable and/or surface potential.
- Solve the implicit equation (using either numerical or analytical approximation) to evaluate the state variables in terms of device parameters and bias conditions.
- Evaluate surface potential (and/or inversion charge) in terms of the state variable.

Previous Accomplished Work (I)

$$\left(V_{GS}-\phi_{ms}-V\right)-V_T\log\left(\frac{4L_{Di}^2}{R^2}\right)=\frac{Q}{C_{ox}}+V_T\log\left(\frac{Q}{Q_0}\right)+V_T\log\left(\frac{Q+Q_0}{Q_0}\right)$$

$$Q_0=\frac{4\varepsilon_{Si}V_T}{R} \qquad V_T=\frac{kT}{q} \qquad L_{Di}^2=\frac{2V_T\varepsilon_{Si}}{qn_i}$$ *(Debye length)*

V → channel potential, R → cylinder radius, ρ → radial direction, ϕ_{ms} → work function difference

$$Q=C_{ox}\left(-\frac{2C_{ox}V_T^2}{Q_0}+\sqrt{\left(\frac{2C_{ox}V_T^2}{Q_0}\right)^2+4V_T^2\log^2\left(1+\exp\left(\frac{V_{GS}-V_0-V}{2V_T}\right)\right)}\right)$$ [2]

$$V_0=\phi_{ms}+V_T\log\left(\frac{4L_{Di}^2}{R^2}\right)$$

Disadvantage:
Deviates significantly in transition region

[2] B.Iniguez, *et al* , *IEEE Trans. Electron Devices*, Aug. 2005, pp:1868–1873.

Previous Accomplished Work (II)

$$C_{ox}\frac{V_{GS}-\phi_{ms}-\phi_s}{V_T}=\frac{R\varepsilon_{Si}}{L_{Di}^2}\exp\left(\frac{\phi_0+\phi_s-2V}{2V_T}\right)$$

$$\phi_s=V_{GS}-\phi_{ms}-2V_TW_0\left(\frac{R\varepsilon_{Si}}{2L_{Di}^2C_{ox}}\exp\left(\frac{V_{GS}+\phi_0-2V-\phi_{ms}}{2V_T}\right)\right)$$

[3] W_0→ *Lambert Function*

$$\phi_0=\frac{1}{2}\left[(\phi_{0\max}+\phi_{0a})-\sqrt{(\phi_{0\max}-\phi_{0a})^2+\delta\phi_{0\max}\phi_{0a}}\right]$$

$$\phi_{0\max}=V+V_T\ln\left(\frac{4L_{Di}^2}{R^2}\right)\qquad \phi_{0a}=V_{GS}-\phi_{ms}$$

Disadvantage:
Use of piecewise model and smoothing functions

[3] J.He, *et al*, *Solid State Electron*, July 2007, pp:802–805.

Previous Accomplished Work (III)

$$\ln\beta - \ln(1-\beta^2) + s\beta^2 \big/ (1-\beta^2) - G = 0 \quad \beta \in (0,1)$$

$s = 2\varepsilon_{si}\ln(1 + t_{ox}/R)/\varepsilon_{ox}$ $\quad G = (V_{GS} - \phi_{ms} - V)/V_T - \ln(2L_{Di}/R)$ *and t_{ox}→oxide thickness*

$$z = \sqrt{\left(\frac{1}{2s^2}\right)^2 + \left(\frac{1}{s^2}\right)\ln^2\left(1+e^G\right)} - \frac{1}{2s^2} \quad [4] \qquad z = \frac{\beta^2}{1-\beta^2}$$

Use correction steps to increase accuracy of the initial guess z using 2nd order Newton Rhapson method

Disadvantage:
Use of piecewise model and smoothing functions
What happens when $G \approx 0$? $z \approx 0$

[4] B.Yu, H.Lu, M.Liu and Y.Taur, *IEEE Trans. Electron Device* , Oct. 2007, pp: 2715-2722.

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Previous Accomplished Work (IV)

$$\alpha = \frac{1}{1+\frac{2}{\eta}W_0\left(\frac{1}{2}\sqrt{1-\alpha}\,\eta e^{\upsilon/2}\right)} \qquad [5]$$

$\alpha = 1-\beta^2$ $\quad$ *β defined as in* [4]

$$y = z - \frac{z(z-1)}{1+z} + \frac{z(z-1)^2}{2(1+z)^3} - \frac{(z-1)^3(z-2z^2)}{6(1+z)^5} + \frac{z(6z^2-8z+1)(z-1)^4}{24(1+z)^7} - \frac{z(24z^3-58z^2+22z-1)(z-1)^5}{120(1+z)^9}$$
$$+\frac{z(120z^4-444z^3+328z^2-52z+1)}{720(1+z)^{11}} - \frac{z(720z^5-3708z^4+4400z^3-1452z^2+114z-1)}{5040(1+z)^{13}}$$

$z = x/e$
valid for $x \le 8$

$$y = L_1 - L_2 + \frac{l_2}{L_1} + \frac{L2(L_{2-2})}{2L_1^2} + \frac{L_2(6-9L_2+2L_2^2)}{6L_1^3} + \frac{L_2(-12+36L_2-22L_2^2+3L_2^3)}{12L_1^4} + \frac{L_2(60-300L_2+350L_2^2-125L_2^3+12L_2^4)}{60L_1^5}$$

$L_1 = ln(x)$
$L_2 = lnln(x)$
valid for $x>8$

Disadvantage:
Cannot be evaluated analytically

[5] H.Morris *et al*, *IEEE UIGM Proceedings,* June 2006, pp:117-121.

Present Modeling Strategy

$$\ln \beta - \ln(1-\beta^2) + s\beta^2/(1-\beta^2) - G = 0 \quad (1)$$

s is a process parameter and G depends on applied bias as defined in [4] and shown in slide 7

$$\ln\left(\frac{\beta^*}{1-(\beta^*)^2}\right) + s\left(\frac{\beta^*}{1-(\beta^*)^2}\right) - G = 0 \quad (2)$$

$$y + se^{y} = G \quad (3)$$

$$y = G - W_0(e^{G}s) \quad (4)$$

$$\ln\left(\frac{\beta^*}{1-(\beta^*)^2}\right) = G - W_0(e^{G}s) \quad (5)$$

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Present Modeling Strategy (contd)

$$\frac{\beta^*}{1-(\beta^*)^2} = \exp\left[G - W_0(e^G s)\right] = \frac{1}{k}$$ 6

$$W_0(x) = 0.04 + 0.665[1 + 0.0195\ln(1+x)]\ln(1+x)$$ [6] 7

$$\beta^* = \frac{2}{k + \sqrt{k^2 + 4}}$$ 8

$$f(\beta) = \ln\beta - \ln(1-\beta^2) + s\beta^2/(1-\beta^2) - G$$ 9

$$\beta_1 = \beta^* - \frac{f(\beta^*)/f_1(\beta^*)}{1 - f(\beta^*)f_2(\beta^*)/2f_1^2(\beta^*)}$$ 10

f_1 → 1^{st} derivative and f_2 → 2^{nd} derivative of f w.r.t. β

[6] A.Ringwald *et al,* QCDINS, *Comput. Phys. Commun.*, Nov. 2000, pp: 267–305.

Comparison of Correction Methods

Here we show the correction form used in the present model and [7] is more efficient than that in [4]

$$\frac{f(\beta)/f_1(\beta)}{1 - f(\beta)f_1(\beta)/2f_1^2(\beta)}$$

form of correction method in present model [8]

$$f(\beta)/f_1(\beta)\left(1 - f(\beta)f_1(\beta)/2f_1^2(\beta)\right)^{-1}$$

$$\approx f(\beta)/f_1(\beta)\left(1 + f(\beta)f_1(\beta)/2f_1^2(\beta)\right)$$

correction method as in [4], (excluding 3rd derivatives)

$$f(\beta)f_1(\beta)/2f_1^2(\beta) << 1$$

valid only if

[7] A.R.Boothroyd , *et al*, *IEEE Trans. on CAD of Integrated Circuits and Syst.*, Dec. 1991, pp:1512– 1529.

[8] F.B.Hildebrand, "*Introduction to Numerical Analysis*", 2nd edition, McGraw-Hill.

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Results Obtained from the Analytical Modeling

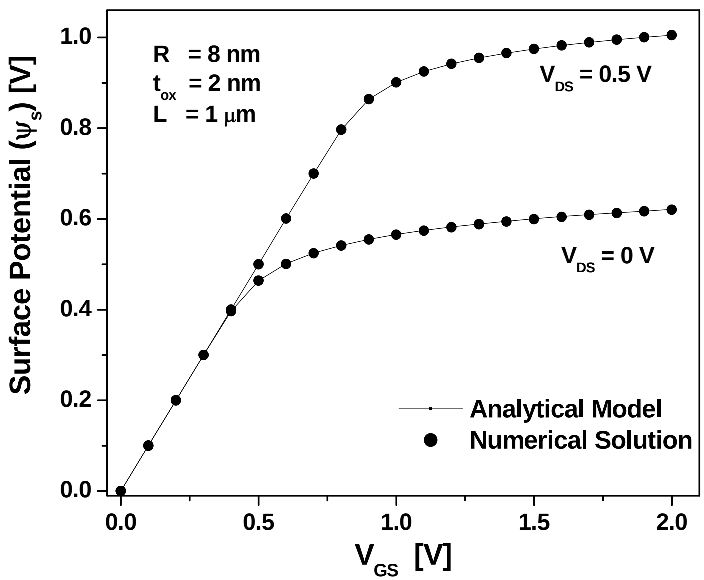

Fig.2. Comparison of surface potential as obtained from the proposed analytical solution and exact numerical method.

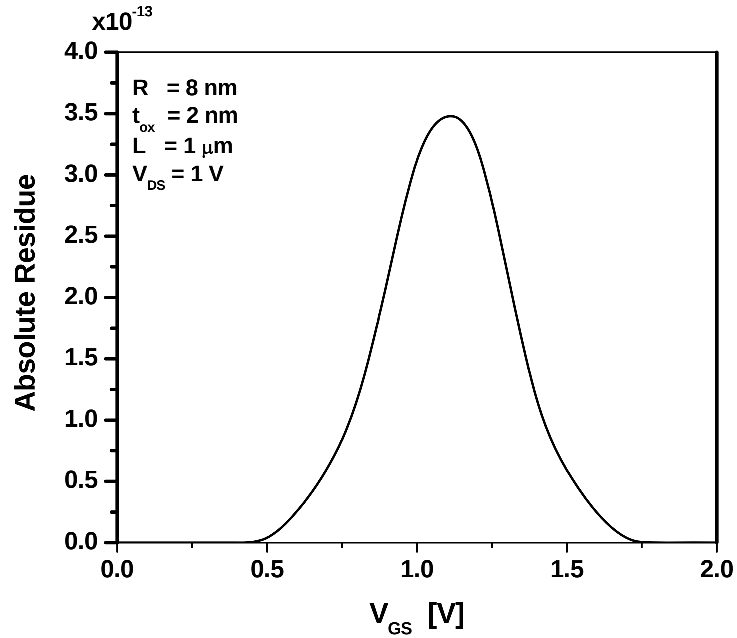

Fig.3. Plot of absolute residue in β values, obtained from plugging the results from our analytical model in (1).

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Results Obtained from the Analytical Modeling (contd)

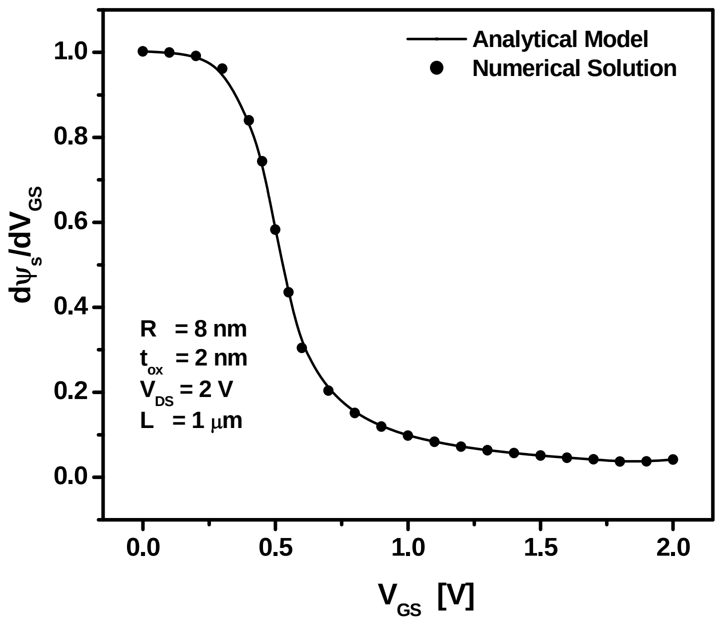

Fig.4. Comparison of first derivative of surface potential obtained from the analytical solution for different values of V_{GS}, with that from numerical solution.

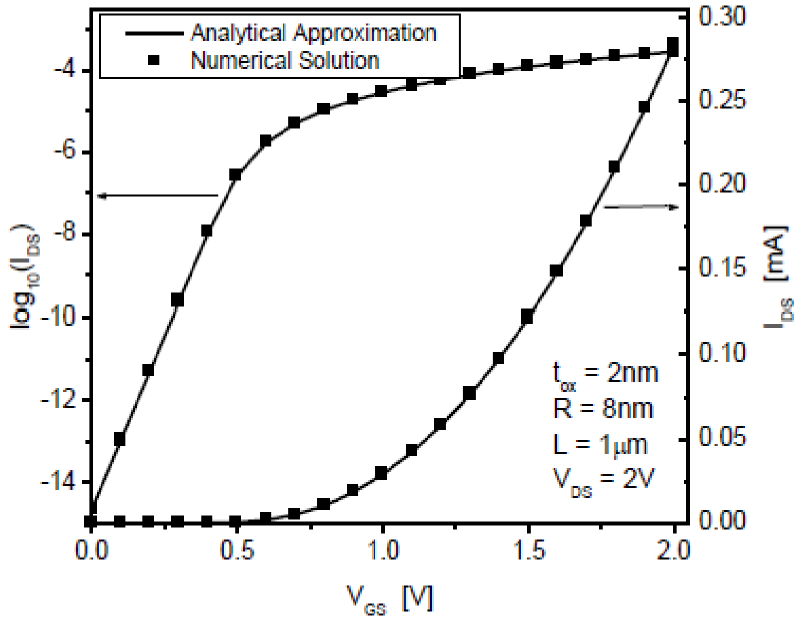

Fig.5. Comparison of I_{DS} (both log and linear scale) as obtained from surface potential values calculated numerically and from our analytical solution for different V_{GS} using equations in [9].

[9] G. Dessai, A.Dey, G.Gildenblat and G.D.J.Smit, *Solid State Electron,* May 2009, pp:548-556.

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Results Obtained from the Analytical Modeling (contd)

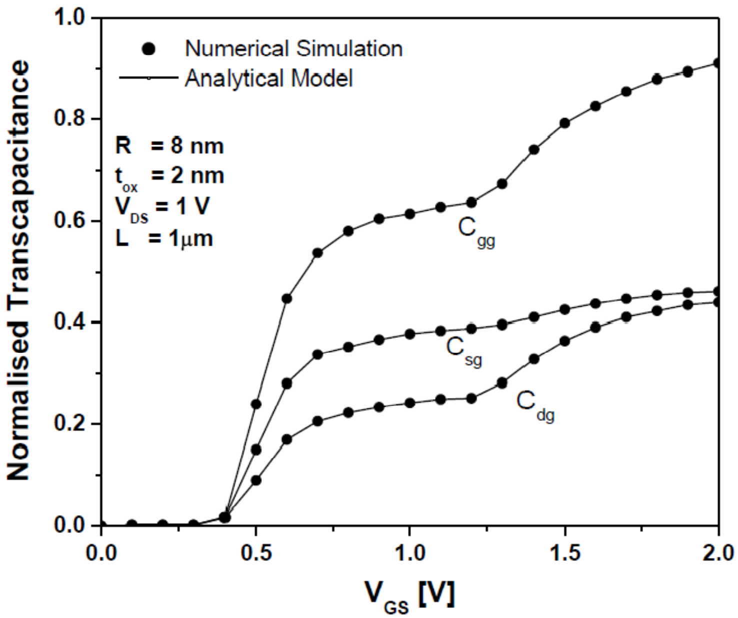

Fig.6. Comparison of normalized transcapacitances obtained from our analytical model and numerical simulations using capacitance equations in [9].

Approximation	CPU time	Fails if V_{GS}-V_{FB} <
[4]	0.22	-1.3V
Present Work	0.214	Works in all cases

Table 1. enumerates the computational efficiency and applicability of the present model and that presented in [4].

[4] B.Yu, H.Lu, M.Liu and Y.Taur, *IEEE Trans. Electron Device* , Oct. 2007, pp: 2715-2722.

Conclusion

A simple analytic solution to the surface potential for and un-doped surrounding-gate MOSFET is presented. The salient features of the present model include

- The solution is numerically robust and is valid in all regions of operation of the device.
- The solution does not use piecewise models and empirical functions to join them.
- The solution is computationally more efficient than that in [4], yet maintaining the same accuracy.

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