Unified Analytical Model of Threshold Voltage in Symmetric and Asymmetric Double-Gate MOSFETs

D. Munteanu[1], J.L. Autran[1], S. Harrison[1,2], T. Skotnicki[2]

[1] L2MP, UMR CNRS 6137, Marseille, France
[2] STMicroelectronics, Crolles, France

www.l2mp.fr
autran, munteanu@up.univ-mrs.fr

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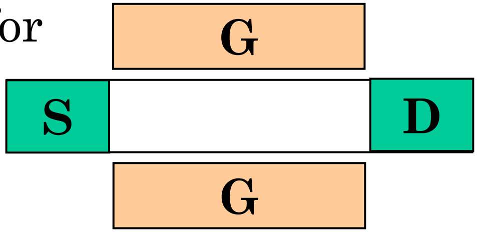
Introduction

- **Double-Gate**: one of the most promising structures for ultimate deca-nanometer scale



- **DG threshold voltage modeling:**
  - V_T definition
  - Mobile charge usually neglected

- **Existing models:**

		Model 1	Model 2	Model 3
Structure	Symmetric	YES	YES	**NO**
	Asymmetric	YES	**NO**	YES
Channel Doping	Intrinsic	YES	YES	YES
	High	**NO**	YES	**NO**
Mobile charge (in Poisson equation)		YES	YES	**NO**

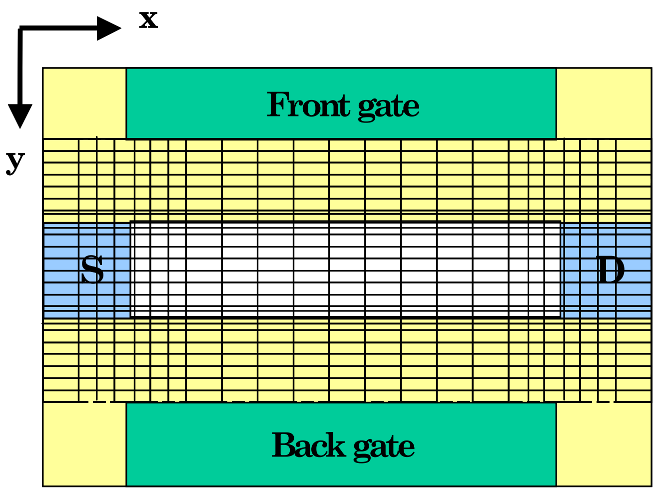
Model 1: *Y. Taur, IEEE TED 48, p. 2861, 2001.*

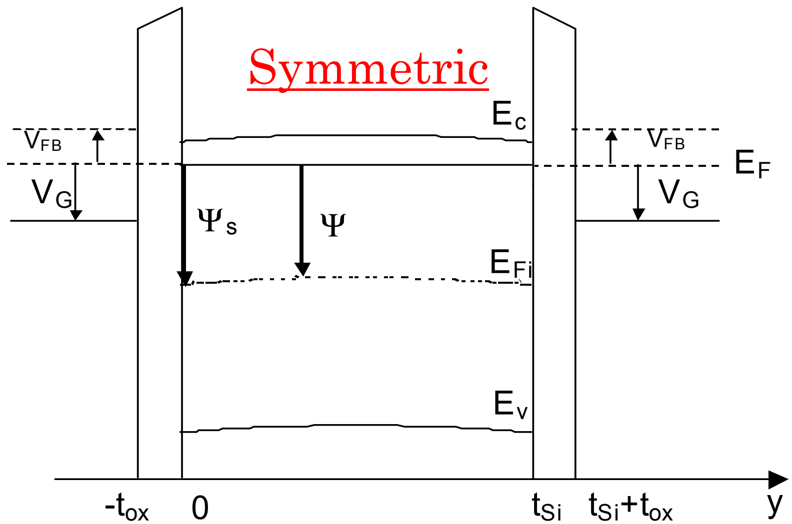
Model 2: *P. Francis et al., IEEE TEI 41, p. 715, 1994.*

Model 3: *K. Suzuki et al., IEEE TEL 42, p. 1940, 1995.*

- **This work: unified V_T model for both symmetric and asymmetric** structures, with doped or undoped bodies and considering the mobile charge

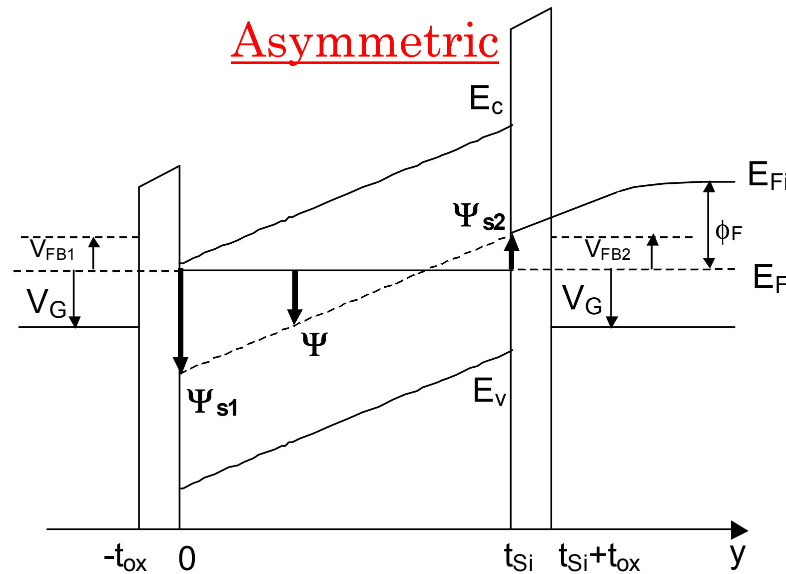
Threshold voltage model — Band Diagram





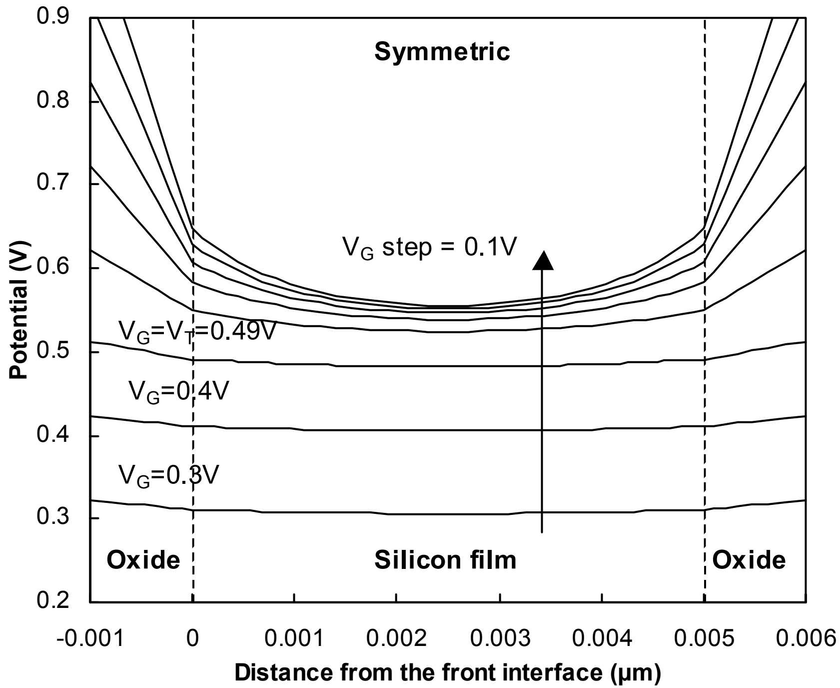
- Long channel model
- Gauss law

$$
\begin{cases}
V_G - V_{FB1} = \dfrac{\varepsilon_{Si}}{\varepsilon_{ox}} t_{ox} E_1 + \Psi_{s1} + \phi_F \\[2ex]
V_G - V_{FB2} = -\dfrac{\varepsilon_{Si}}{\varepsilon_{ox}} t_{ox} E_2 + \Psi_{s2} + \phi_F
\end{cases}
$$

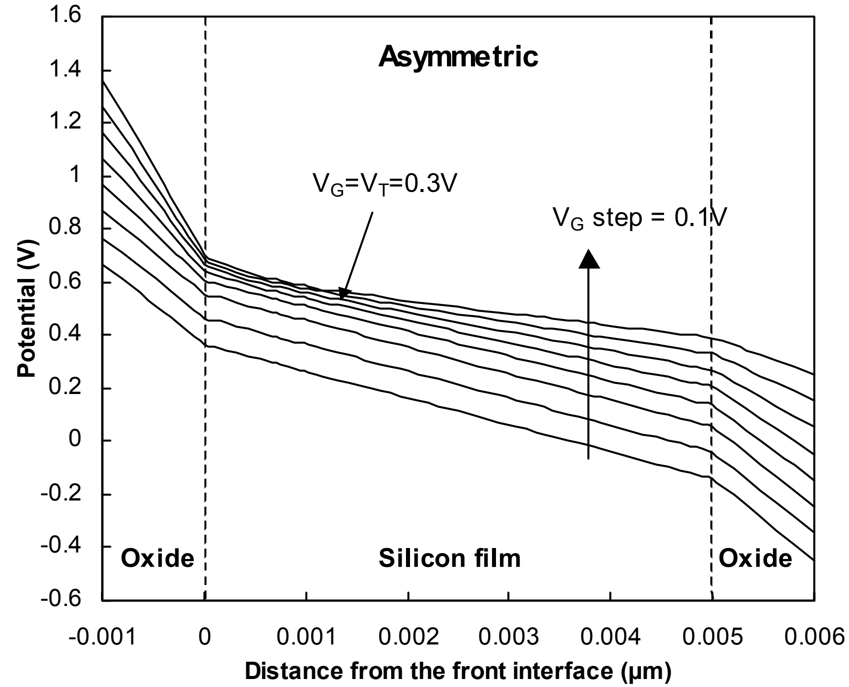


Threshold voltage model — Potential distribution

Symmetric



Asymmetric



- **Potential approximation:** $$\Psi = \Psi_{s1} + \alpha y + \beta y^2$$

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- **Electric field at interfaces:**

$$E_1 = -\frac{d\Psi}{dy}\Big|_{y=0} = -\alpha \qquad E_2 = -\frac{d\Psi}{dy}\Big|_{y=tSi} = -\alpha - 2\beta t_{Si}$$

- **1-D Poisson equation:**

$$\underbrace{\int_0^{t_{Si}} \frac{d^2\Psi}{dy^2}}_{E_1 - E_2} = \int_0^{t_{Si}} \frac{qN_A}{\varepsilon_{Si}} + \frac{1}{\varepsilon_{Si}} \int_0^{t_{Si}} q\, n_i e^{\frac{q\Psi}{kT}}$$

Q_i (inversion charge)

⇓

$$\beta(Q_i) = \frac{qN_A}{2\varepsilon_{Si}} + \frac{Q_i}{2\varepsilon_{Si} t_{Si}} \qquad \alpha(Q_i) = \frac{V_{FB1} - V_{FB2}}{2\gamma t_{ox} + t_{si}} - \beta(Q_i)\, t_{Si}$$

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Threshold voltage model

- **Conventional MOSFET: band bending is $2\times\phi_F$**
- **Double-Gate MOSFET: $\psi_s \neq 2\times\phi_F$**
- **Threshold voltage definition:**

$V_G = V_T$ when $\frac{d^2 I_D}{dV_G^2}$ **is maximum** ⇒ $\frac{d^3 I_D}{dV_G^3} = 0$

- **Drain current:**

$$I_D = \frac{W}{L}\mu_n \int_0^{V_D} Q_i(V)\,dV$$

low V_D approximation

⇒ $\frac{d^3 Q_i}{dV_G^3} = 0$

- **Surface potential**

$$Q_i = \int_0^{t_{Si}} q\, n_i\, e^{\frac{q\Psi(y)}{kT}}\, dy$$

$$\Psi = \Psi_{s1} + \alpha y + \beta y^2$$

$$\Rightarrow \quad \Psi_{s1} = \frac{kT}{q} \ln\left(\frac{Q_i}{q n_i}\right) + \Psi_1$$

$$\text{where } \Psi_1 = -\frac{kT}{q} \ln \int_0^{t_{Si}} e^{\frac{q}{kT}(\alpha y + \beta y^2)}\, dy$$

- **Ψ_1 can be expressed analytically:**

$$\Psi_1 = \frac{e^{-\frac{\alpha^2}{4 u_{th} \beta}} \sqrt{\pi u_{th}}\ \mathrm{Erfi}\left(\frac{\alpha}{2\sqrt{u_{th}\beta}}\right)}{2\sqrt{\beta}} - \frac{e^{-\frac{\alpha^2}{4 u_{th} \beta}} \sqrt{\pi u_{th}}\ \mathrm{Erfi}\left(\frac{\alpha + 2 t_{Si} \beta}{2\sqrt{u_{th}\beta}}\right)}{2\sqrt{\beta}}$$

- **Ψ_1 is linear as a function of Q_i**

$$\Psi_1 = M + N \times Q_i$$

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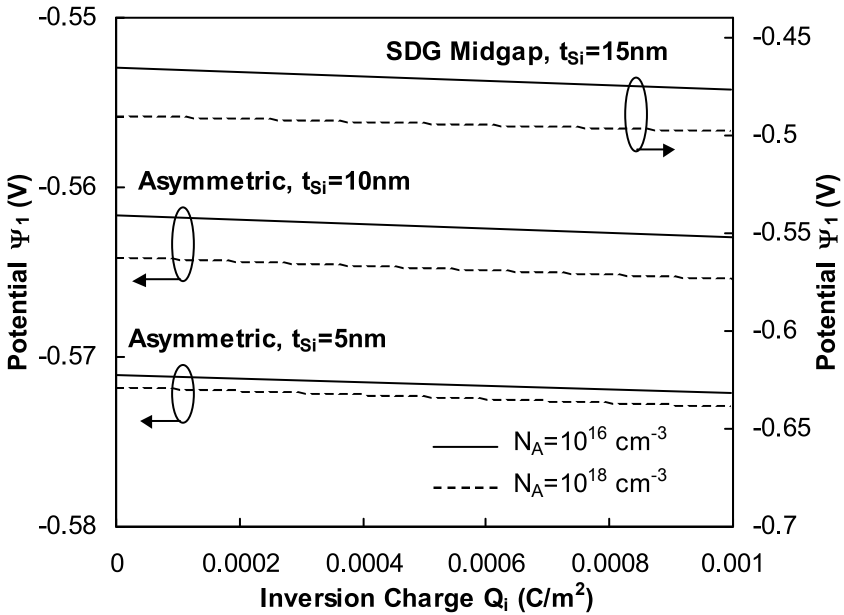
$$\Psi_1 = M + N \times Q_i$$

$$M = \Psi_{1\,max}$$

$$N = \frac{\partial \Psi_1}{\partial Q_i} = \frac{\Delta \Psi_1}{\Delta Q_i}$$

$$\begin{cases} \Psi_{1\,max} = \Psi_1(Q_i = Q_{i\,min}) \\ \Psi_{1\,min} = \Psi_1(Q_i = Q_{i\,max}) \\ Q_{i\,min} = q n_i{}^2 \frac{t_{Si}}{N_A} \\ Q_{i\,max} = (V_G - V_T) C_{ox} = \frac{kT}{q} C_{ox} \end{cases}$$



- Surface potential

$$\Psi_{s1} = \frac{kT}{q} \ln\left(\frac{Q_i}{q n_i}\right) + M + NQ_i$$

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Threshold voltage model

$$\frac{d^3 Q_i}{dV_G^{\,3}} = 0$$

$$\Psi_{s1} = \frac{kT}{q}\ln\left(\frac{Q_i}{qn_i}\right) + M + NQ_i$$

$$V_G - V_{FB1} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} t_{ox} E_1 + \Psi_{s1} + \phi_F$$

$$\Rightarrow \quad Q_{iT} = \frac{\frac{kT}{q} C_{ox}}{1 - 2N \frac{kT}{q} C_{ox}}$$

Inversion charge at threshold

- **α and β at threshold**

$$\alpha(Q_{iT}) = \frac{V_{FB1} - V_{FB2}}{2\gamma t_{ox} + t_{si}} - \frac{qN_A t_{Si}}{2\varepsilon_{Si}} + \frac{\frac{kT}{q} C_{ox}}{2\varepsilon_{Si}\left(1 - 2N\frac{kT}{q}C_{ox}\right)}$$

$$\beta(Q_{iT}) = \frac{qN_A}{2\varepsilon_{Si}} + \frac{\frac{kT}{q} C_{ox}}{2\varepsilon_{Si} t_{Si}\left(1 - 2N\frac{kT}{q}C_{ox}\right)}$$

- **Surface potential at threshold**

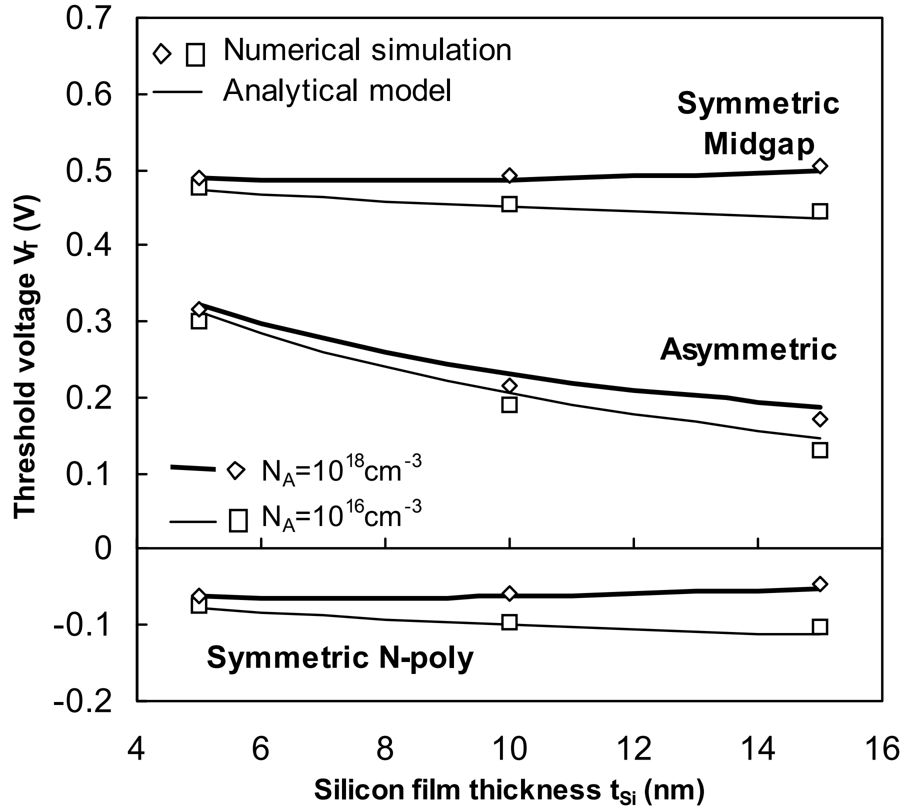
$$\Psi_{s1T} = \frac{kT}{q}\ln\left[\frac{\frac{kT}{q}C_{ox}}{q\,n_i\,(1 - 2N\frac{kT}{q}C_{ox})}\exp\left(M - \frac{N\frac{kT}{q}C_{ox}}{1 - 2N\frac{kT}{q}C_{ox}}\right)^{-1}\right]$$

- **Final expression of the threshold voltage**

$$V_T = V_{FB1}\frac{\gamma t_{ox} + t_{Si}}{2\gamma t_{ox} + t_{Si}} + V_{FB2}\frac{\gamma t_{ox}}{2\gamma t_{ox} + t_{Si}} + \Psi_{s1T} + \gamma t_{ox}\, t_{Si}\,\beta(Q_{iT}) + \phi_F$$

Model validation (1)

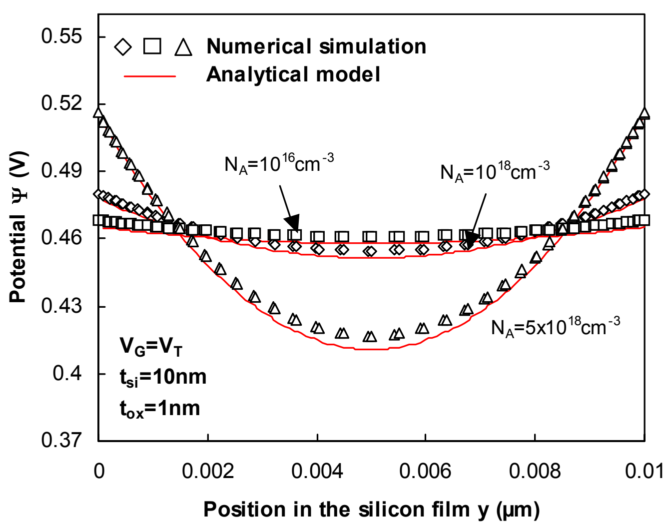
Comparison with numerical simulation



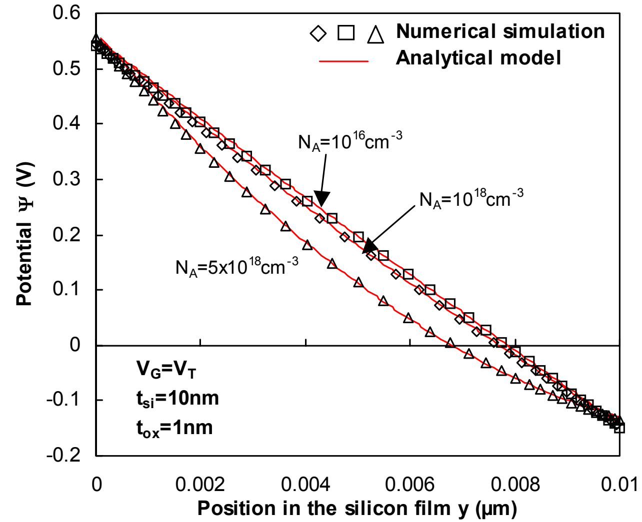
Model validation (2)

Potential distribution

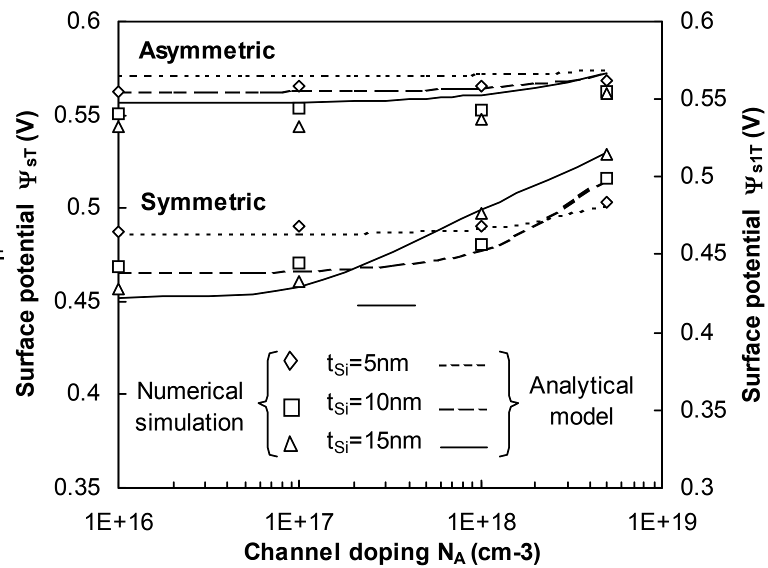
Symmetric DG



Asymmetric DG



Surface potential



Conclusion

- A unified analytical model for the threshold voltage in long channel Double-Gate devices is developed

- Compared to previous models our approach gives a unique expression for the threshold voltage applying to both symmetric and asymmetric DG structures with both doped and undoped films

- The model takes into account the mobile charge in the Poisson equation

- The model is used to analyze the threshold voltage sensitivity to the silicon thickness and the gate requirements for nano-scale integration