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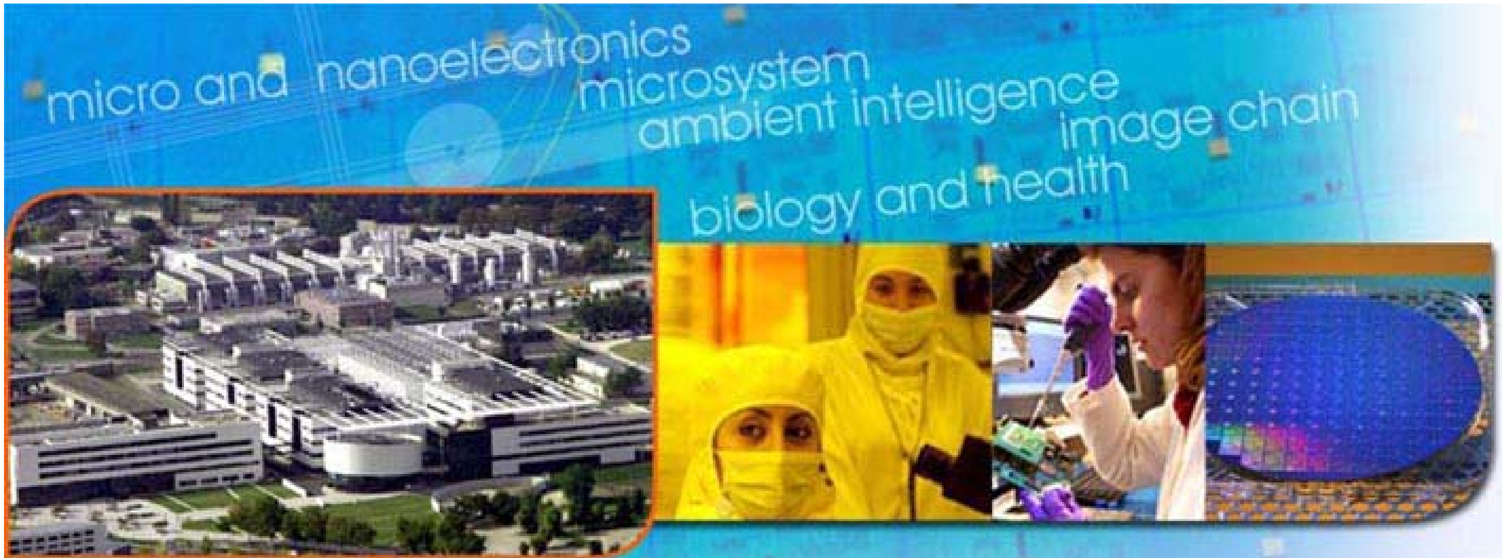

2010

A Continuous Compact Model of Short-Channel Effects for Undoped Cylindrical Gate-All-Around MOSFETs

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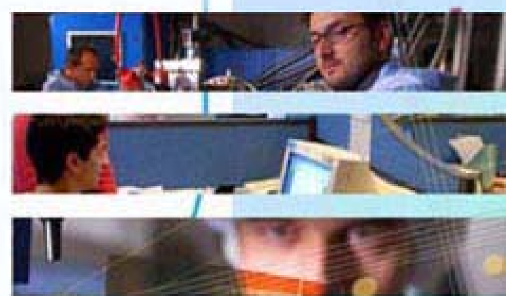

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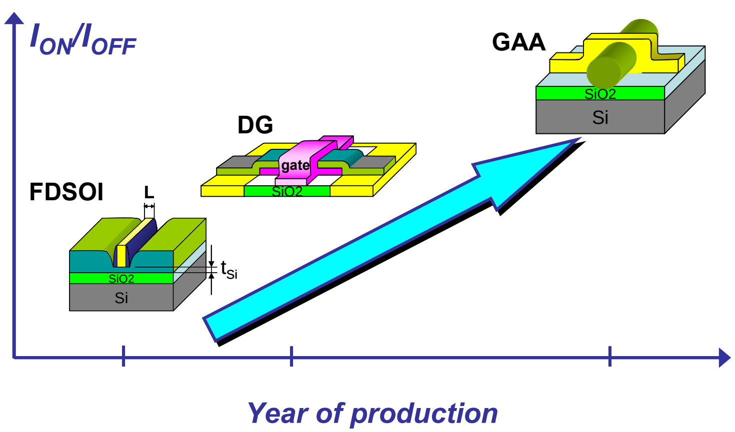
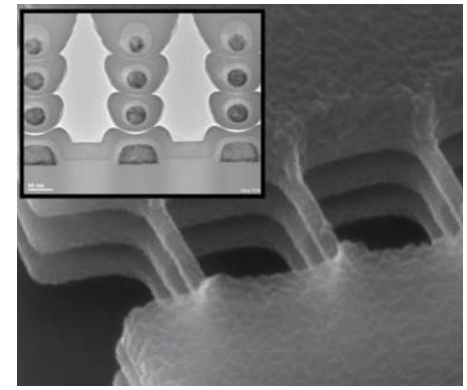
Outline

- General Context
- Short-Channel Effects Modeling
- Short-Channel Model
    - 2D Potential Distribution
    - Threshold Voltage roll-off
    - DIBL & Subthreshold Swing Degradation
    - Channel Length Modulation
- Short-Channel Correction (Results)
- Conclusion

General Context



Gate-All-Around MOSFETs are becoming a relevant solution to reduce Short-Channel Effects observed in classical CMOS devices.



- **Excellent gate control ability**: I_{ON}/I_{OFF} is increased.
- Undoped silicon **improves variability**.
- **Current density increased** by making stacked nanowires MOSFETs [1].

Objective: *Evaluate device performances in term of circuit design*

Designers must have a predictive compact model

[1] E. Dornel et al., *Appl. Phys. Lett.*, vol. 91, Dec. 2007.

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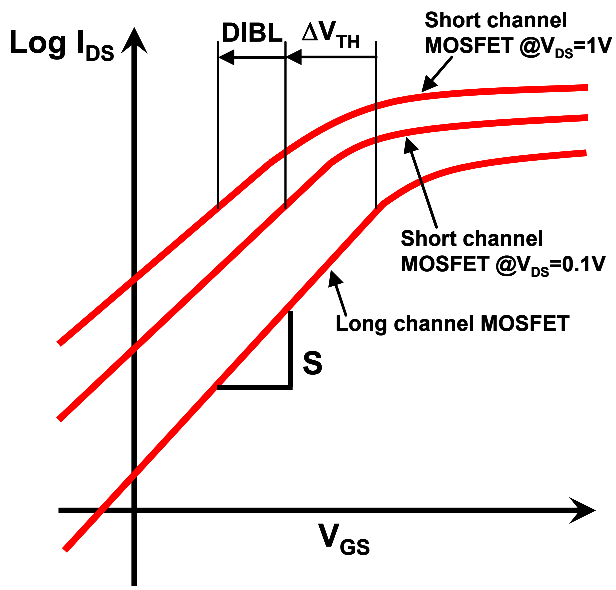
Short-Channel Effects Modeling

1. **Threshold voltage roll-off**

Long-channel threshold voltage + **Short-channel threshold voltage**

2. **DIBL (*Drain Induced Barrier Lowering*)**
3. **Subthreshold swing degradation**
4. **Channel length modulation**



→ **Implementing Short-Channel Effects in a long-channel *I-V* model core**

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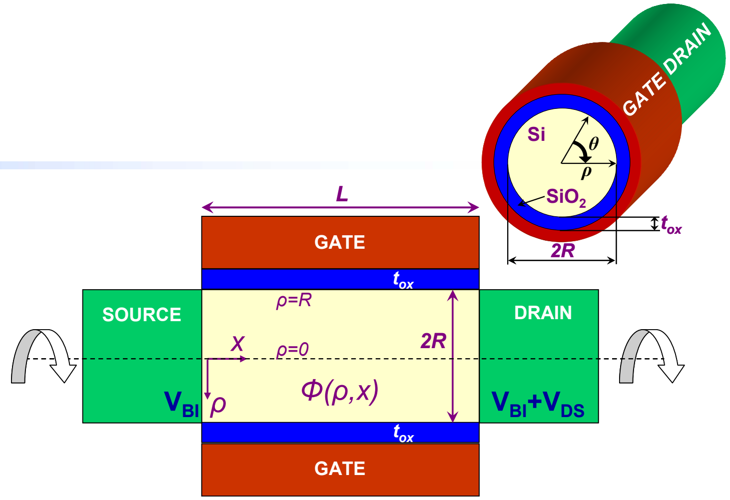
2D Potential Distribution



2D cylindrical Poisson's equation:

$$\frac{\partial^2\phi_{2D}(x,\rho)}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial\phi_{2D}(x,\rho)}{\partial\rho}+\frac{\partial^2\phi_{2D}(x,\rho)}{\partial x^2}=\frac{q}{\varepsilon_{si}}n_i e^{\frac{\phi_{2D}(x,\rho)}{ut}}$$

Potential split [4]:

$$\phi_{2D}(x,\rho)=\phi_0(\rho)+\phi_1(x,\rho)$$

$$\frac{\partial^2\phi_0(\rho)}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial\phi_0(\rho)}{\partial\rho}=\frac{q}{\varepsilon_{si}}n_i e^{\frac{\phi_0(\rho)-V_{ch}}{ut}}$$

$$\frac{\partial^2\phi_1(x,\rho)}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial\phi_1(x,\rho)}{\partial\rho}+\frac{\partial^2\phi_1(x)}{\partial x^2}=0$$

Final solution:

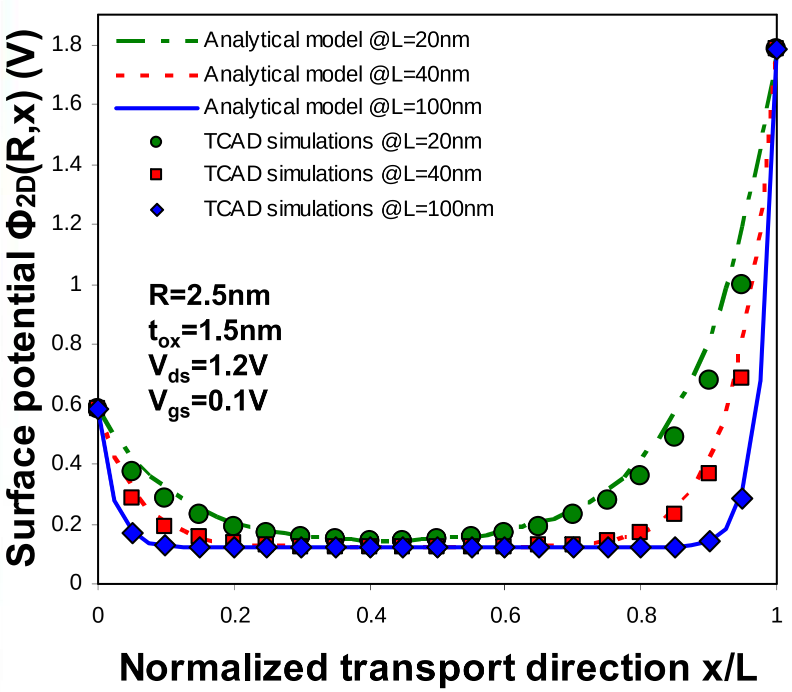
$$\phi_{2D}(x,\rho)=\phi_0(\rho)[1-S(x)]+V_{BI}\,S(x)+V_{DS}\frac{\sinh\left(\frac{\lambda x}{R}\right)}{\sinh\left(\frac{\lambda L}{R}\right)}$$

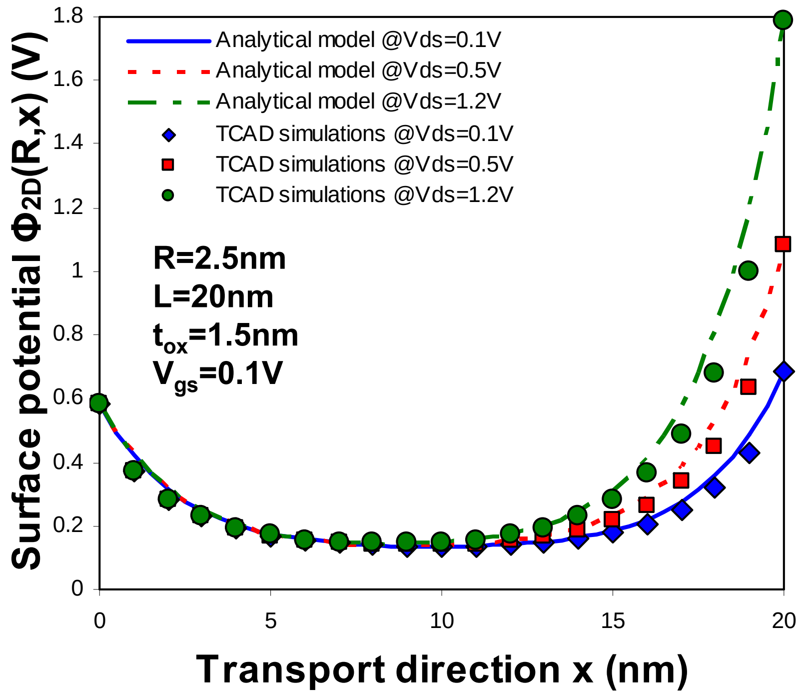
$$\begin{cases} S(x)=exp\left(\frac{-\lambda x}{R}\right)+\left(1-exp\left(\frac{-\lambda L}{R}\right)\right)\frac{sinh\left(\frac{\lambda x}{R}\right)}{sinh\left(\frac{\lambda L}{R}\right)} \\ \lambda=\frac{-C_{ox}R}{\varepsilon_{si}}\frac{J_0(\lambda)}{J_1(\lambda)} \end{cases}$$

[4] H. Abd El Hamid et al., *IEEE Trans. Electron Devices*, vol. 54, no. 3, Mar. 2007.

2D Potential Distribution

Results





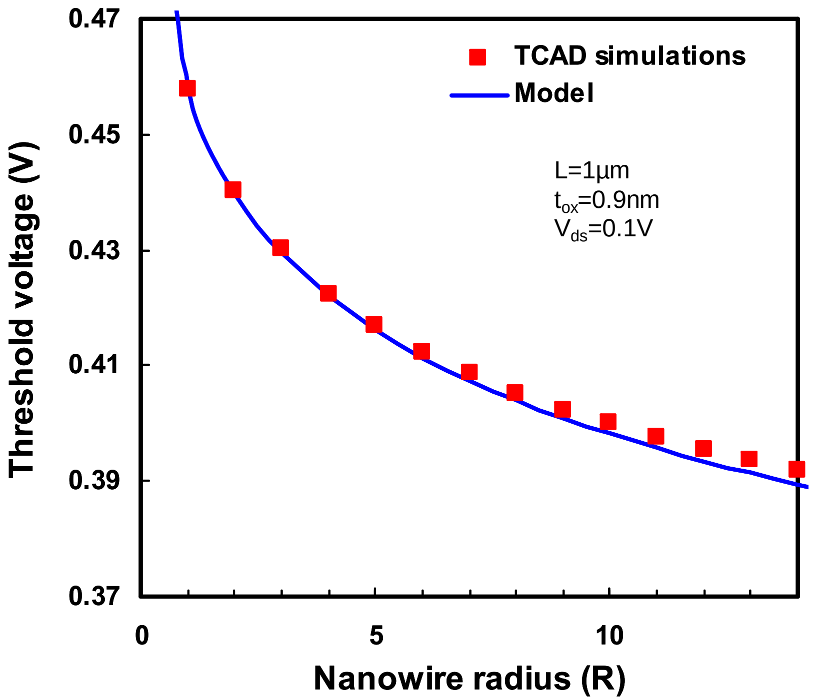
Threshold Voltage roll-off – Long Channel V_{TH}

From [3], the **threshold condition** is defined by setting:

$$I_{DS} \overset{@threshold}{=} \frac{2\pi R}{L} 10^{-7}$$

Long-channel threshold voltage:

$$V_{TH}^{Long} = \Delta\phi + ut \ln\left(\frac{2}{q\, n_i\, R\, \mu\, ut} 10^{-7}\right)$$

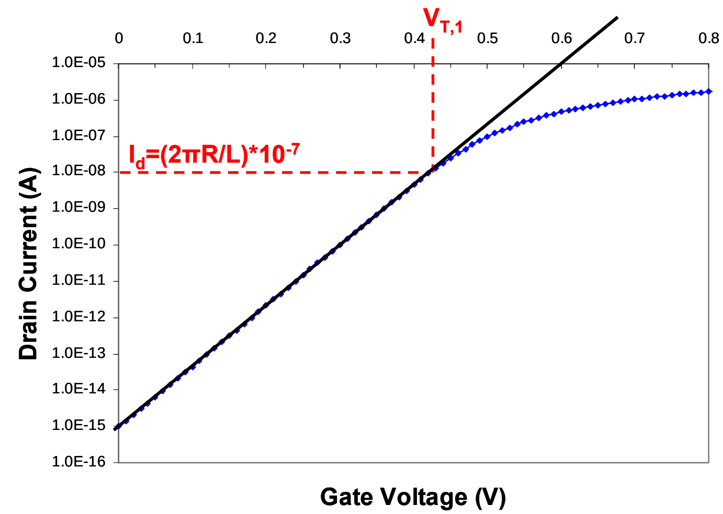


[3] B. Yu et al., *IEEE Trans. Electron Devices*, vol. 54, no. 10, Oct. 2007.

Threshold Voltage roll-off – Short Channel V_{TH}

Subthreshold drain current :

$$I_{DS} = \mu \pi R \frac{ut\left(1-exp\left(\frac{-V_{DS}}{ut}\right)\right)}{\int_0^L \frac{1}{\int_0^R q\, n_i exp\left(\frac{\phi_{2D}(x,\rho)}{ut}\right) d\rho} dx}$$



- The same method is used to solve both the **Long** and the **Short-Channel threshold voltages**:

$$I_{DS} \overset{@\text{threshold}}{=} \frac{2\pi R}{L} 10^{-7}$$

- The **current constant method** extracts V_{TH} at the frontier of subthreshold and moderate inversion regions.

Threshold Voltage roll-off – Short Channel V_{TH}

2D potential is constant in the radial direction ρ:

$$\frac{ut\left(1-exp\left(\frac{-V_{DS}}{ut}\right)\right)}{exp\left(\frac{-\phi_0(R)}{ut}\right)\int_0^L \exp\left(\frac{-\phi_1(x,R)}{ut}\right)dx} = \frac{2\cdot 10^{-7}}{\mu\, q\, n_i\, R\, L}$$

The integral $\int_0^L exp\left(\frac{-\phi_1(x,R)}{ut}\right)dx$ cannot be solved analytically.

Analytic solution:

$$Y = \int_0^L exp\left(\frac{-\phi_1(x,R)}{ut}\right)dx \approx 2\frac{R}{\lambda}\ln(ut) - \frac{R}{\lambda}\ln\left(ut + V_{BI} - \phi_0(R)\right) - \frac{R}{\lambda}\ln\left(ut + V_{BI} - \phi_0(R) + V_{DS}\right) + L$$

Linearization:

$\ln\left(Y\left(V_{GS}, V_{DS}\right)\right) = a\cdot V_{GS} + b$ with $V_{GS} = V_{TH}^{Short} \in \left[V_{TH}^{Long}; V_{TH}^{Long} - 0.1\text{V}\right]$

Threshold Voltage roll-off – Short Channel V_{TH}

Threshold voltage approximated equation:

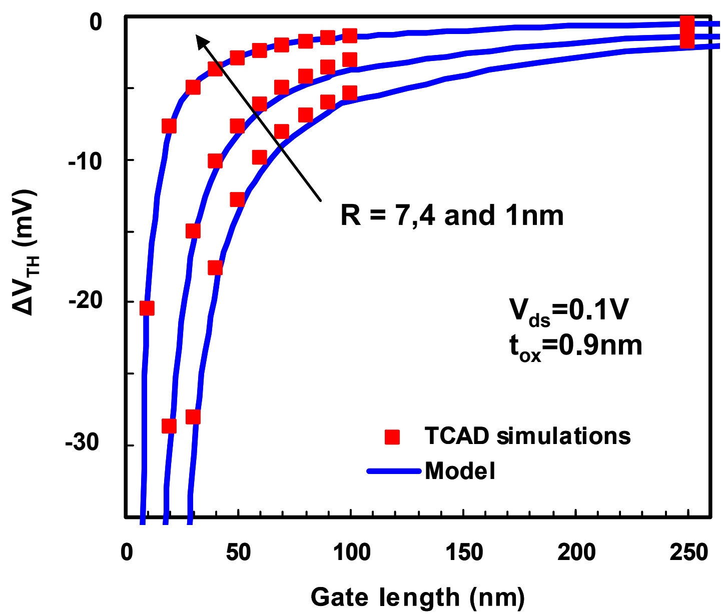
$$\frac{ut\left(1-exp\left(\frac{-V_{DS}}{ut}\right)\right)}{exp\left(\frac{\Delta\phi-V_{GS}}{ut}+a\cdot V_{TH}{}^{Short}+b\right)}=\frac{2\cdot 10^{-7}}{\mu\, q\, n_i\, R\, L}$$

Short-channel threshold voltage:

$$V_{TH}{}^{Short}=\frac{1}{1-a}\left[\Delta\phi+b+\text{ut}\ \ln\left(\frac{2}{q\, n_i\, R\, L\, \mu\, ut}10^{-7}\right)\right]$$

Threshold voltage roll-off:

$$\Delta V_{TH}=V_{TH}{}^{Short}-V_{TH}{}^{Long}$$

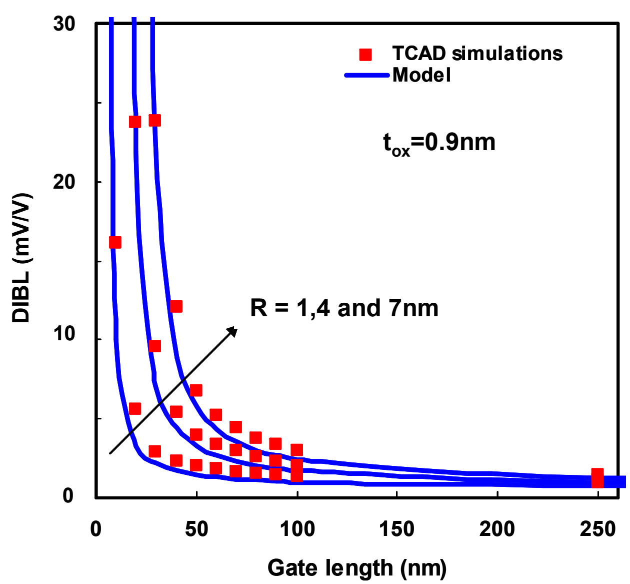


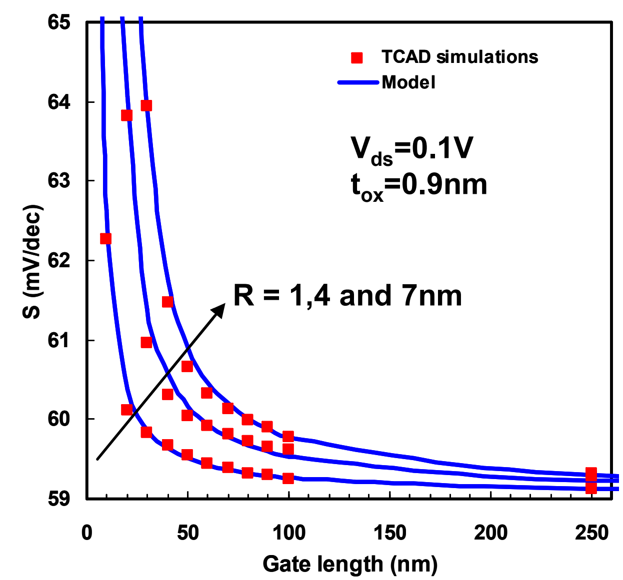
DIBL & Subthreshold Swing degradation

$$I_{DS} = \mu \pi R q n_i \frac{ut\left(1-exp\left(\frac{-V_{DS}}{ut}\right)\right)}{exp\left(\frac{\Delta\phi - V_{GS}}{ut} + \ln\left(Y\left(V_{GS}, V_{DS}\right)\right)\right)}$$

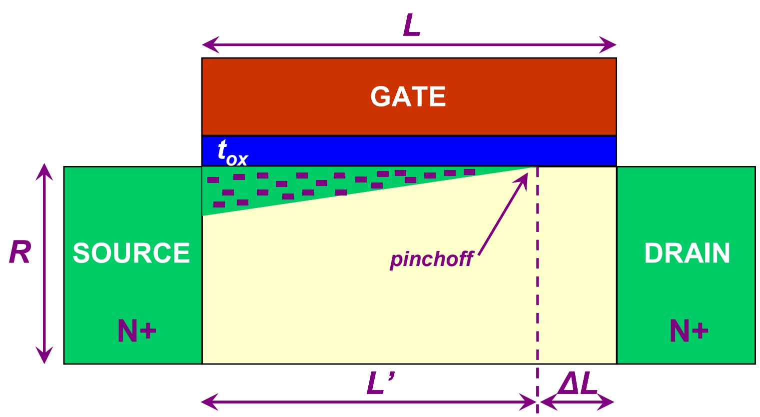
$$DIBL = V_{TH}^{Short}\left(@V_{DS} = 1.0\text{V}\right) - V_{TH}^{Short}\left(@V_{DS} = 0.1\text{V}\right)$$

$$S = \frac{\partial V_{GS}}{\partial \log I_{DS}}$$





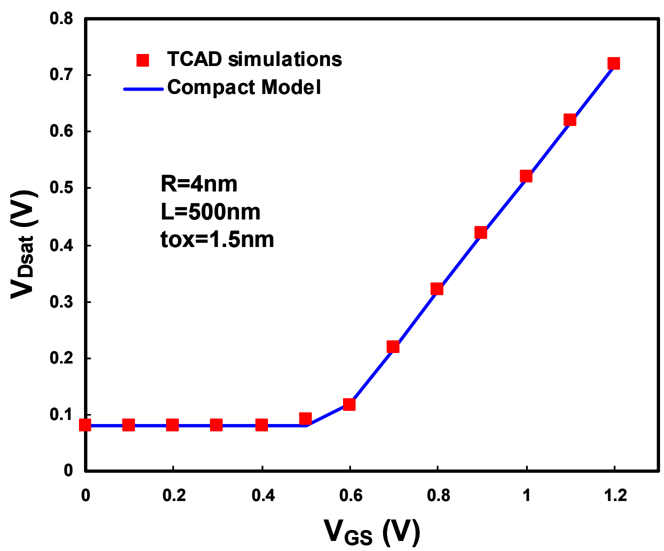
Channel Length Modulation



$$L' = L - \Delta L$$

$$\Delta L = \lambda \ln\left(1 + \frac{V_{DS} - V_{DSeff}}{V_E}\right)$$

$$V_{DSeff} = \frac{V_{DS}}{\left(1 + \left(\frac{V_{DS}}{V_{Dsat}}\right)^8\right)^{\frac{1}{8}}}$$



$$V_{Dsat} = \frac{\ln\left(1 + exp\left(20 \cdot V_{Dsat}'\right)\right)}{20} + 3ut$$

$$V_{Dsat}' = V_{GS} - \Delta\phi - ut \ln 0.5 - 2ut \ln\left(\frac{2L_{Di}}{R}\right) - 3ut$$

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Short-Channel Correction

The **short-channel correction** is applied in the long-channel model core [3] as:

Subthreshold Swing degradation

V*_TH roll-off + *DIBL

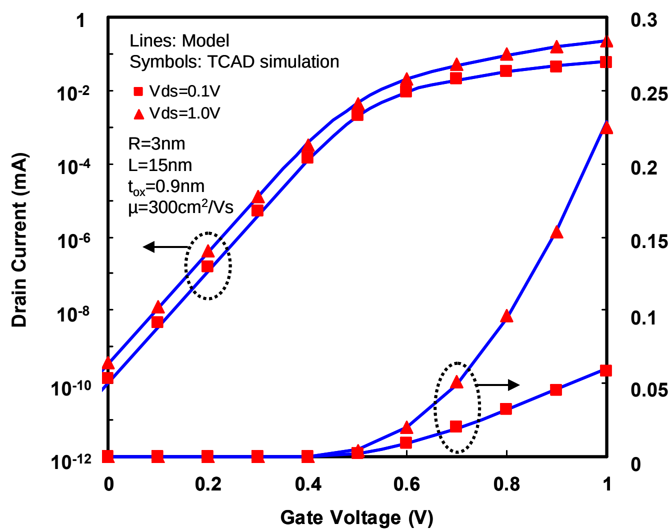
$$(c_1 \cdot S + c_2)\cdot \ln\left(z_{SCE} + z_{SCE}^{2}\right) + \left[2\frac{\varepsilon_{\mathrm{si}}}{\varepsilon_{\mathrm{ox}}}\ln\left(1+\frac{t_{ox}}{R}\right)\right]\cdot z_{SCE} - \frac{V_{GS} - \Delta\phi + \Delta V_{TH} - V_{ch}}{2ut} + \ln\left(\frac{2L_{Di}}{R}\right) = 0$$

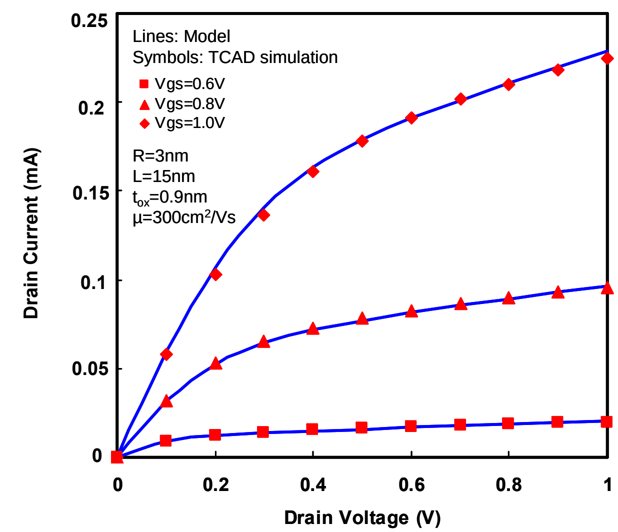
$$I_{DS} = \mu\frac{8\pi\varepsilon_{\mathrm{si}}}{L'}ut^{2}\left[f\left(z_{SCE}\left(V_{ch}=V_{DS}\right)\right) - f\left(z_{SCE}\left(V_{ch}=0\right)\right)\right]$$

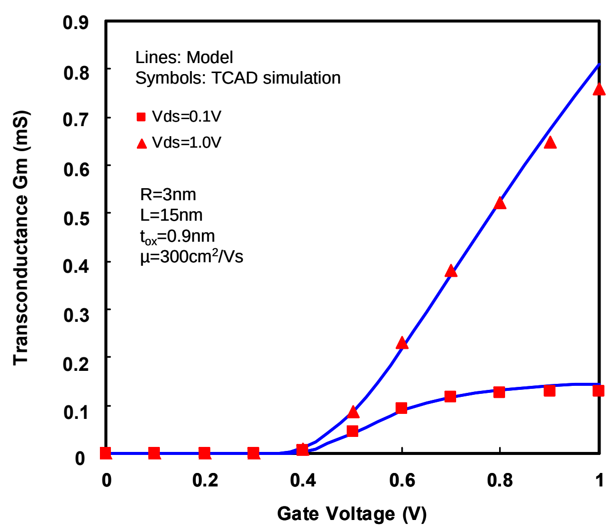
Channel Length Modulation

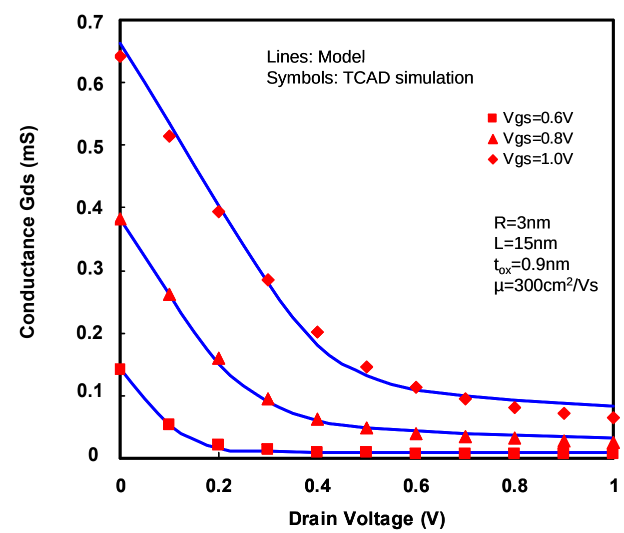
[3] B. Yu et al., *IEEE Trans. Electron Devices*, vol. 54, no. 10, Oct. 2007.

Short-Channel Correction – Results









Conclusion

- Based on a usual V_{TH} extraction method, the threshold voltage is computed both for long and short-channel MOSFETs devices.
- A new **analytical**, **simple** and **accurate** model is developed for:
  - Threshold voltage roll-off
  - DIBL
  - Subthreshold swing degradation
  - Channel length modulation
- A short-channel correction is applied in a surface-potential based model with successful results till L=10nm for R=2.5nm and t_{ox}=0.7nm.
- A unified Short-Channel model is provided for all operative regions and suitable with circuits simulation tools.

Acknowlegments

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