Equivalent Correlation between Short Channel DG & GAA MOSFETs

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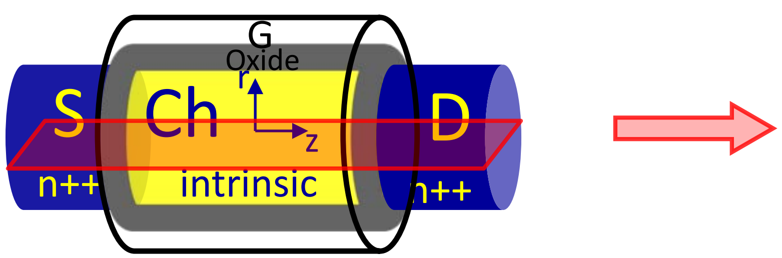
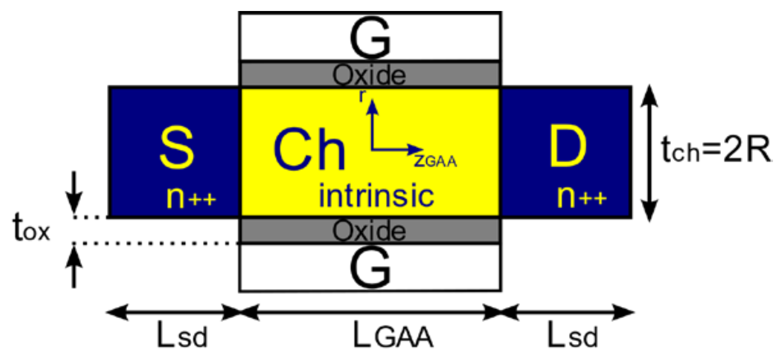
Motivation

- Status quo: Concept of equivalent thickness and capacitance (long channel) [1].
- Goal: Extend 2-D DG compact model [2] to short channel GAA MOSFETs.
- Challenge: Stretch the channel length to equalize electrostatics & short channel behavior.
- Methods: 1. Theory derived from the Laplace's & Poisson's equation.
  2. Concept of equivalent channel length due to equiv. capacitance.





[1] N. Chevillon et al., IEEE TED, Vol. 59, no. 1, pp. 60-71, January 2012.
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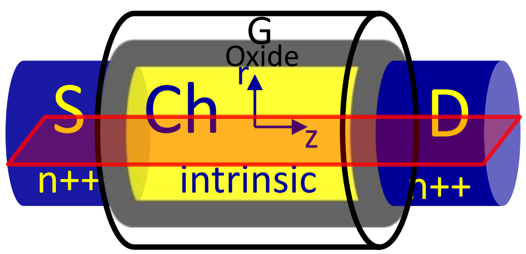

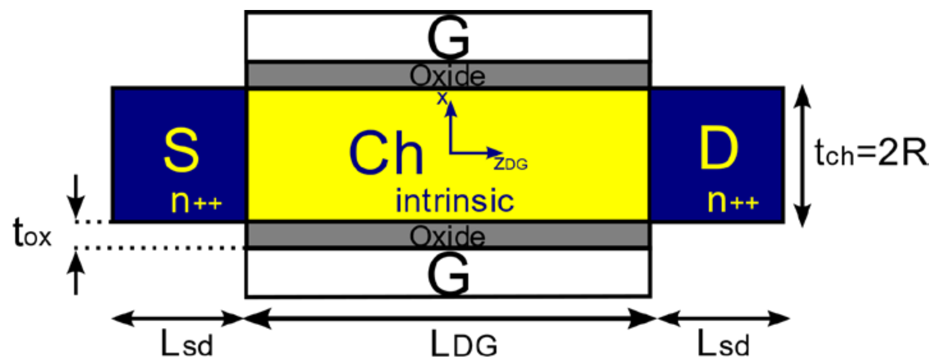

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Outline

1. Introduction
2. Device dimensions dependent equivalent length
3. Simulation & Compact Model Results
4. Conclusion

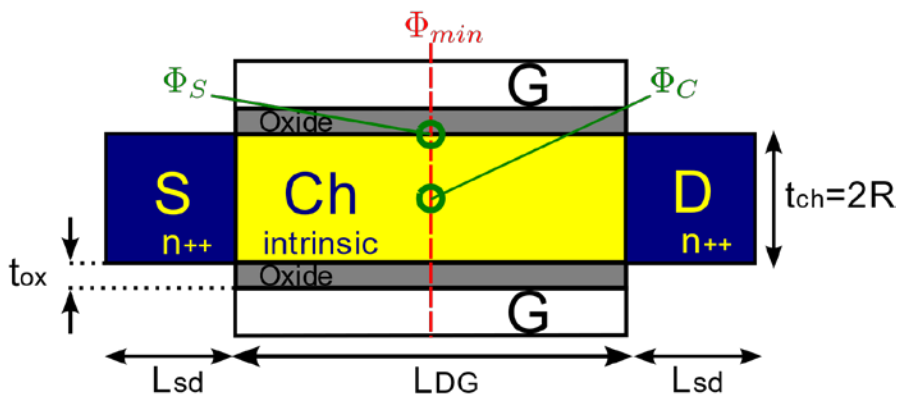
1. Introduction

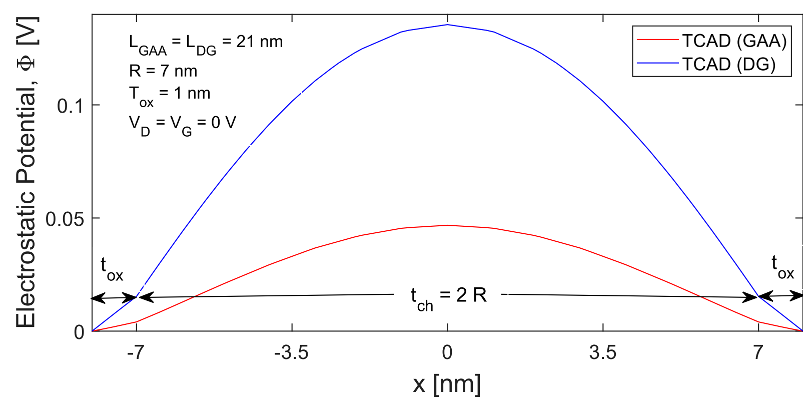
Subthreshold equivalent potential theory:

- Current model [3]: $I_D \propto \int \frac{n_i^2}{N_A} e^{\Phi_{min}/V_t} dx$
- Assumption: Potential barrier through channel thickness is parabolic.

$$\Phi_{min}(x) = \Phi_C - \frac{x^2}{R^2}(\Phi_C - \Phi_S)$$

- Modified current model: $I_D \propto \frac{n_i^2}{N_A} \frac{\sqrt{\pi}}{2} R \cdot e^{\frac{\Phi_C}{V_t}} \cdot \frac{\mathrm{erf}\left(\sqrt{(\Phi_C - \Phi_S)/V_t}\right)}{\sqrt{(\Phi_C - \Phi_S)/V_t}}$



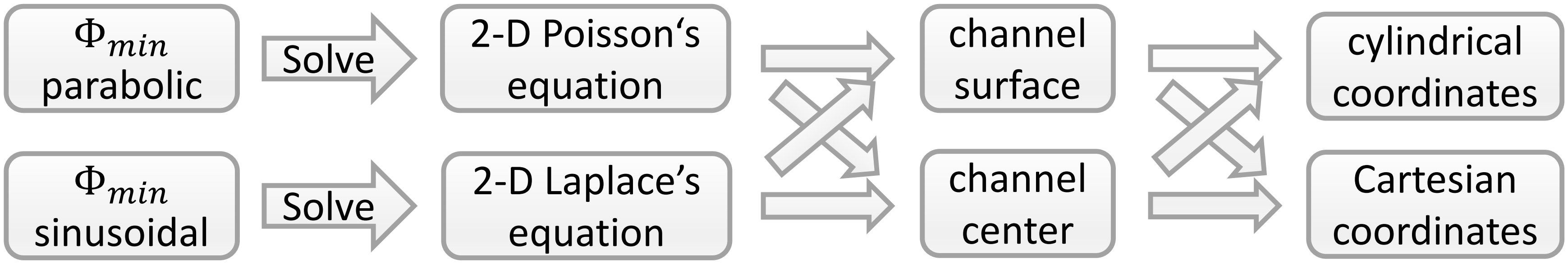


[3] Q. Chen et al., IEEE TED, Vol. 49, no. 6, pp. 1086-1090, June 2002.

2. Device dimensions dependent equivalent length

Two independent derivation methods:

1. Method (=> slightly complicated):



Equate the potential drops $\Phi_{min}(r) = \Phi_{min}(x)$ and compare the potential drops along the channel $\Phi(r,z) \propto e^{\pm z/\lambda}$ with the so-called natural length λ [4,5,6].

Result for Φ if Φ_{min} is sinusoidal [7]:

$$\Phi_{DG} \approx \Phi_C \cdot Cos(\frac{x}{\lambda_{DG}}) \cdot Cosh(\frac{z_{DG}}{\lambda_{DG}})$$

$$\Phi_{GAA} \approx \Phi_C \cdot J_0(\frac{r}{\lambda_{GAA}}) \cdot Cosh(\frac{z_{GAA}}{\lambda_{GAA}})$$

$$z_{DG} \approx \frac{\lambda_{DG}}{\lambda_{GAA}} \cdot z_{GAA} \approx 1.53 \cdot z_{GAA}$$

[4] S.-H. Oh et al., IEEE EDL, Vol. 21, no. 9, pp. 445-447, September 2000.
[5] R. H. Yan et al., IEEE TED, Vol. 39, no. 7, pp. 1704-1710, Jul. 1992.
[6] K. Suzuki et al., IEEE TED, Vol. 40, no. 12, pp. 2326-2329, Dec. 1993.
[7] C. P. Auth et al., IEEE EDL, Vol. 18, no. 2 pp. 74-76, Feb. 1997.

2. Device dimensions dependent equivalent length

Two independent derivation methods:

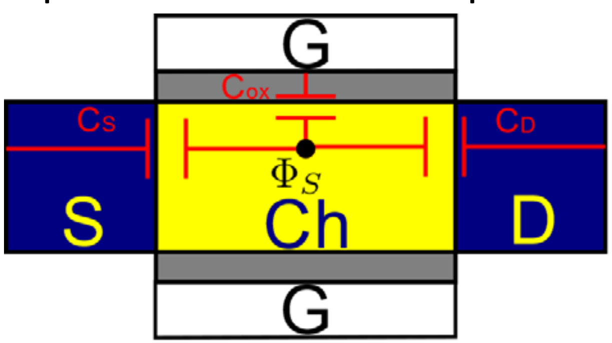
2. Method (=> simpler):

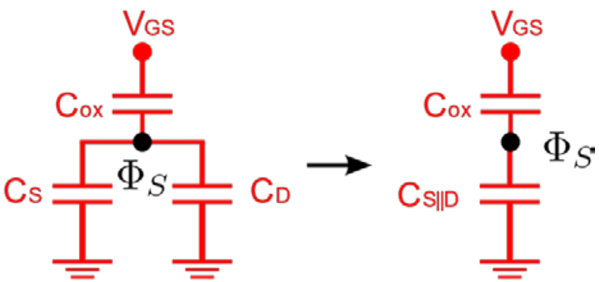
Device's electrostatics are represented by the subthreshold slope

Equalize subthreshold slopes: $S_{sth}^{DG} = S_{sth}^{GAA}$

Lundstrom [8]: $S_{sth} = \eta \log(10)\, V_T$ $\eta^{-1} = \frac{\Phi_S}{V_{GS}} = \frac{\frac{1}{C_{S||D}}}{\frac{1}{C_{ox}} + \frac{1}{C_{S||D}}} = \frac{1}{1 + \frac{C_{S||D}}{C_{ox}}}$

$\Rightarrow$ Ratio of capacitances must be equal!





[8] Lecture: Lundstrom EE-612 F08

2. Device dimensions dependent equivalent length

Two independent derivation methods:

Capacitance	DG		GAA
$C_{S,D}$	$\frac{\epsilon_{Si}\, w\, t_{ch}}{L_{DG}/2}$	=	$\frac{\epsilon_{Si}\, \pi\, R^2}{L_{GAA}/2}$
	―――	=	―――
C_{ox}	$2\frac{\epsilon_{ox}\, w}{t_{ox}} L_{DG}$	=	$2\pi \frac{\epsilon_{ox}}{\ln\left(1+\frac{t_{ox}}{R}\right)} L_{GAA}$

Equivalent channel length:

$$L_{DG} = L_{GAA} * \sqrt{2} * \beta$$

with $\beta = \sqrt{\frac{t_{ox}/R}{ln(1+t_{ox}/R)}}$

In addition:

Equivalent channel width due to equivalent capacitances: $W_{ch} = \frac{\pi\, R}{2} * \sqrt{2} * \beta$

2. Device dimensions dependent equivalent length

⇒ Simulation results match for the center potential: $\Phi^{C}_{GAA} = \Phi^{C}_{DG}$

⇒ Simulation results don't match for the surface potential Φ_S, subthreshold swing and DIBL.

⇒ Capacitance model of Lundstrom has its limitations.

The first method helps out:

Solve the Laplace equation by assuming a sinusoidal shape through the channel thickness! Combining both methods lead to the best match for Φ^S, swing and DIBL.

- Equivalent channel length: $L_{DG} = L_{GAA} * 1.53 * \beta$ with $\beta = \sqrt{\frac{t_{ox}/R}{ln(1+t_{ox}/R)}}$
- Equivalent channel width: $W_{ch} = \frac{\pi R}{2} * 1.53 * \beta$

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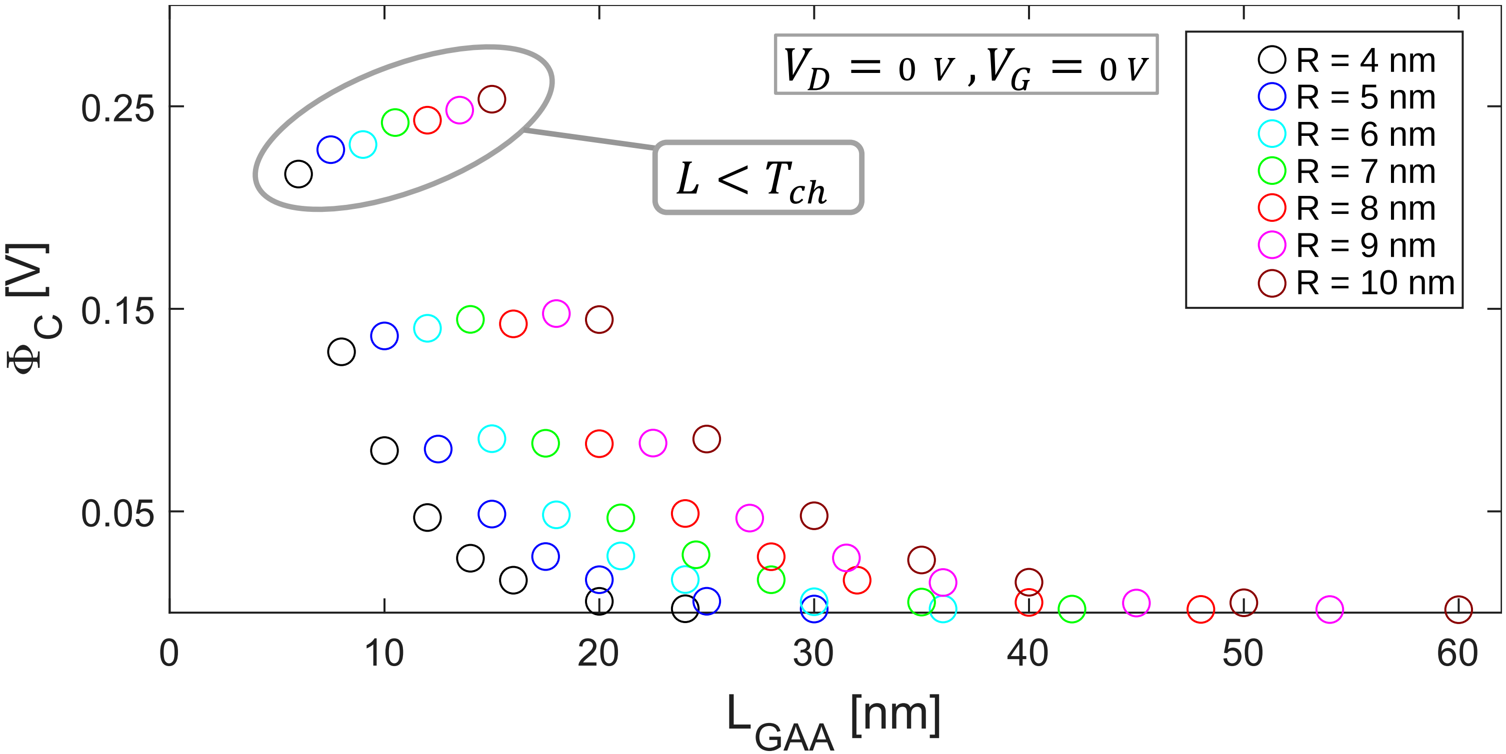
3. Simulation & Compact Model Results

Center potential Φ_C vs. channel length L_{GAA}



$$L_{GAA} = 1.5R, 2R, 2.5R, 3R, 3.5R, 4R, 5R, 6R$$

o TCAD (GAA) * TCAD (DG) + Model

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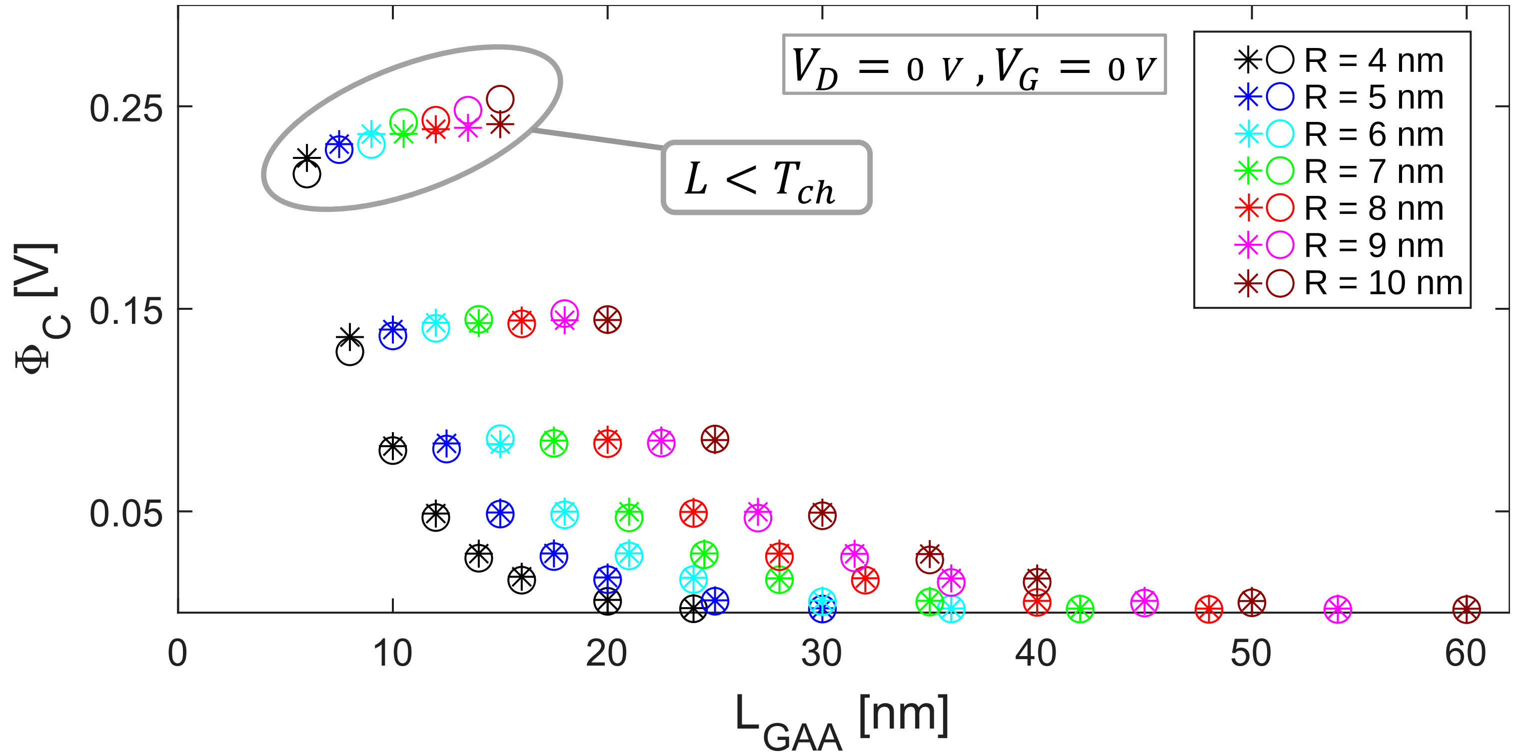

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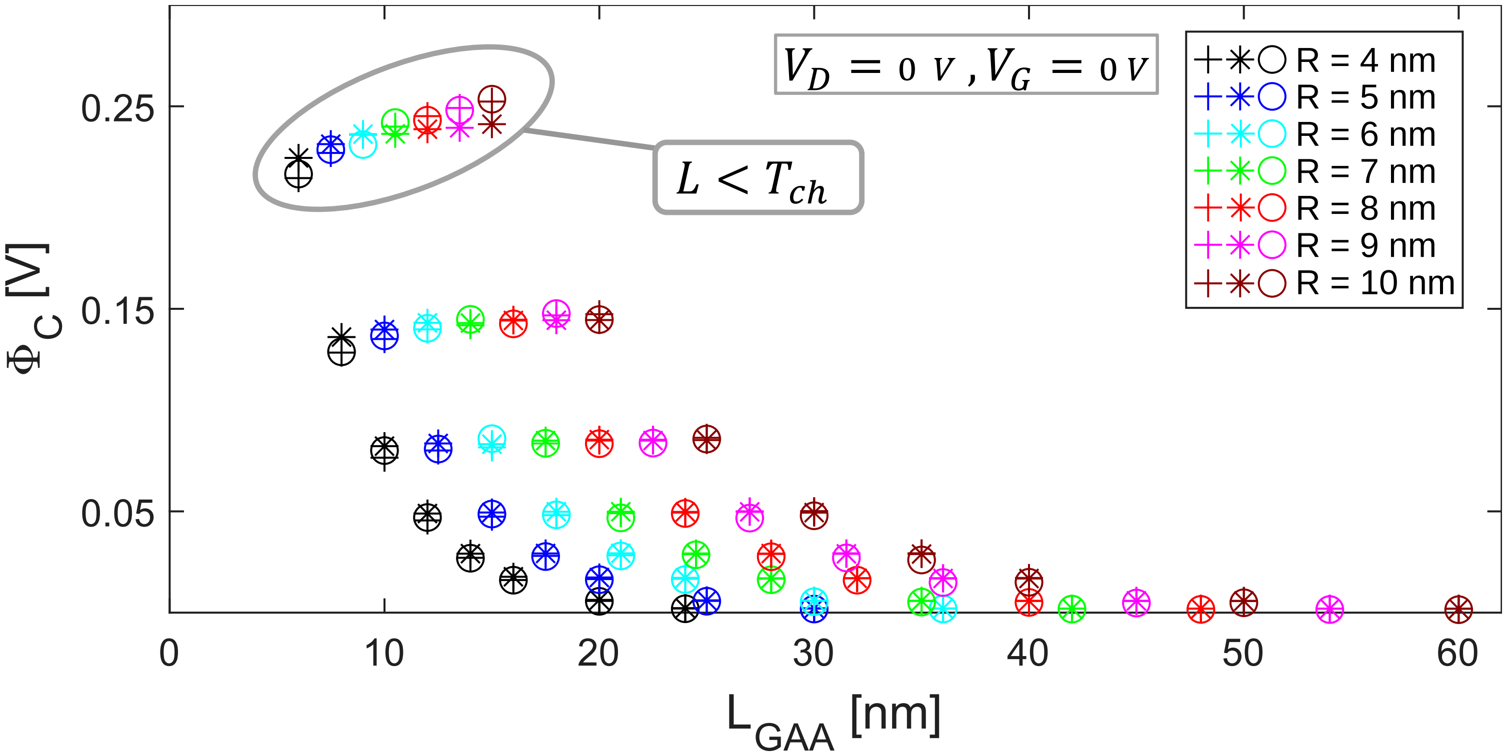

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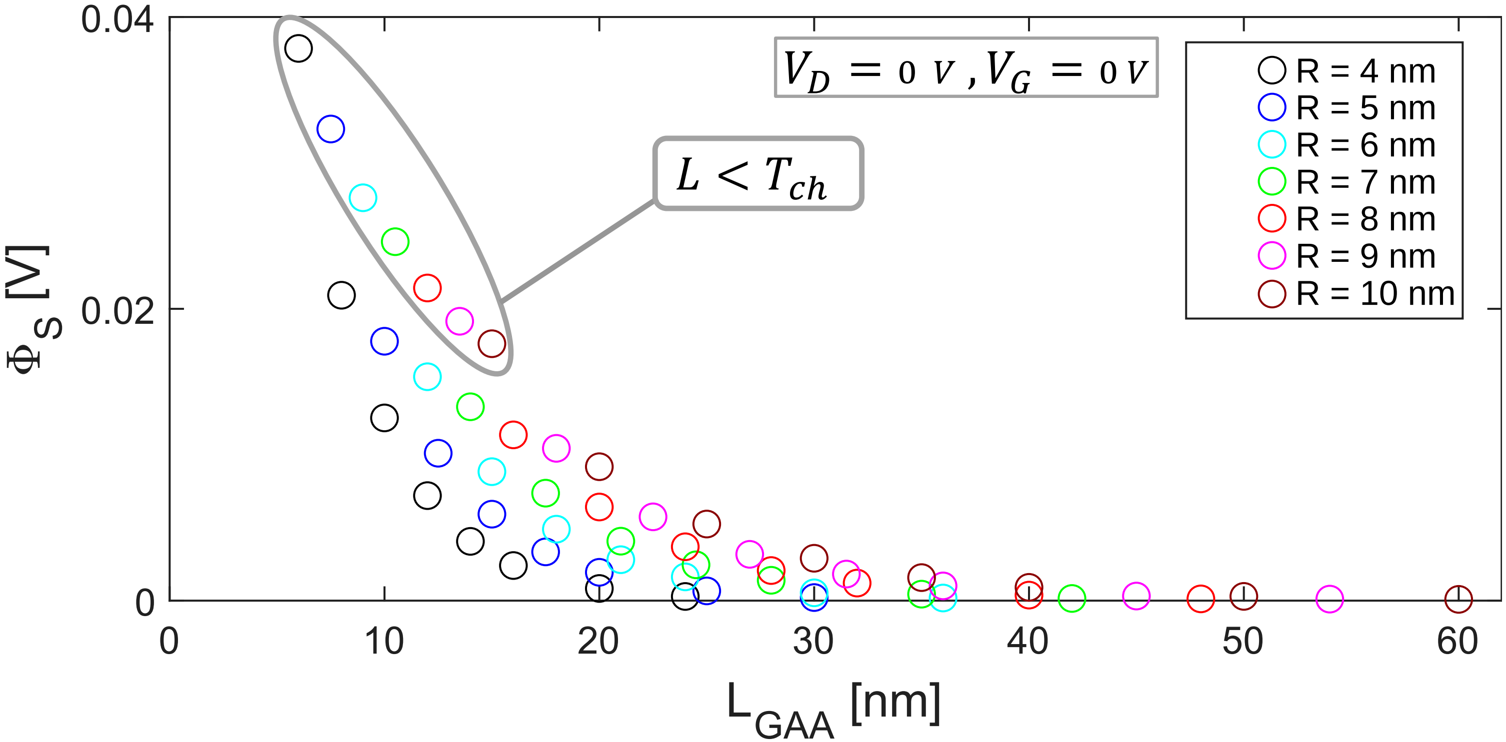
3. Simulation & Compact Model Results

Surface potential Φ_S vs. channel length L_{GAA}



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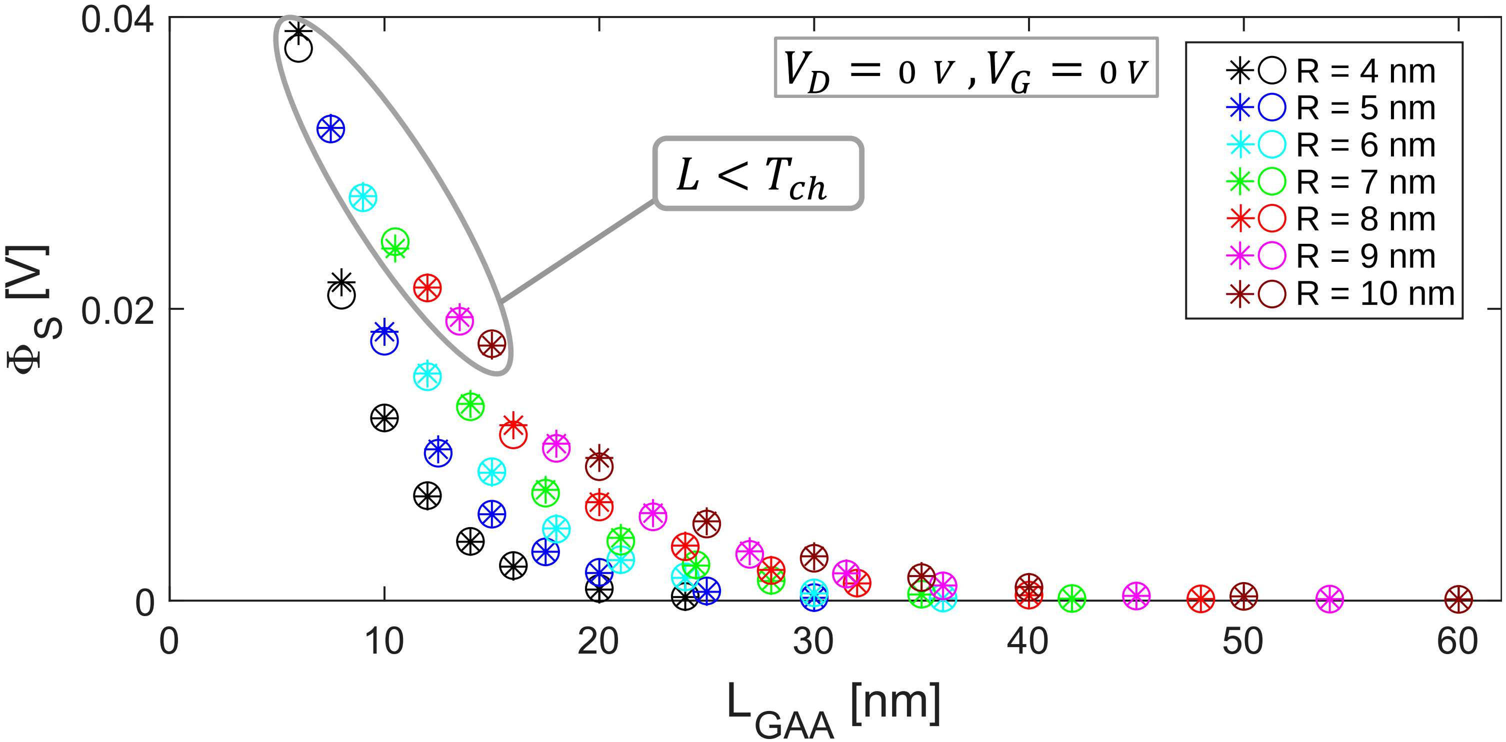

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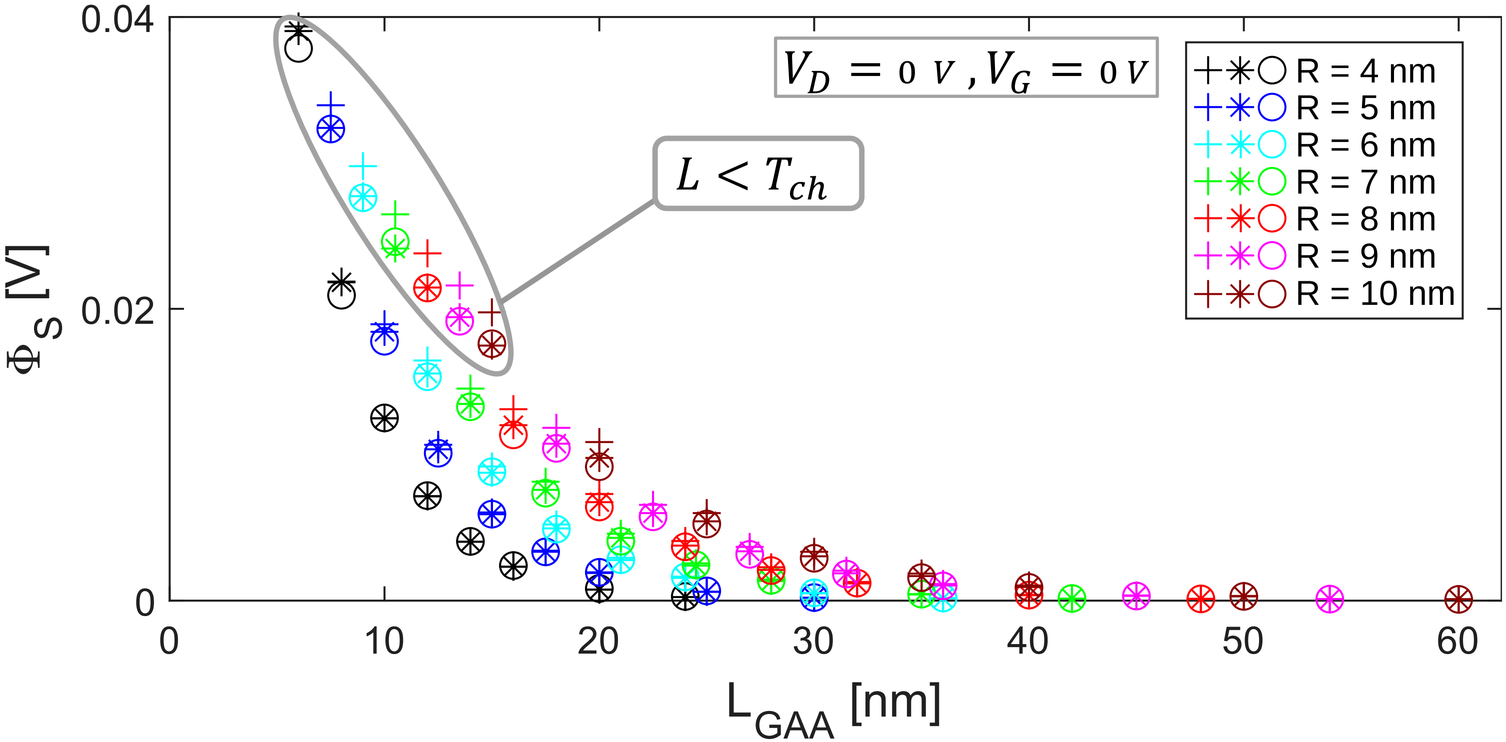

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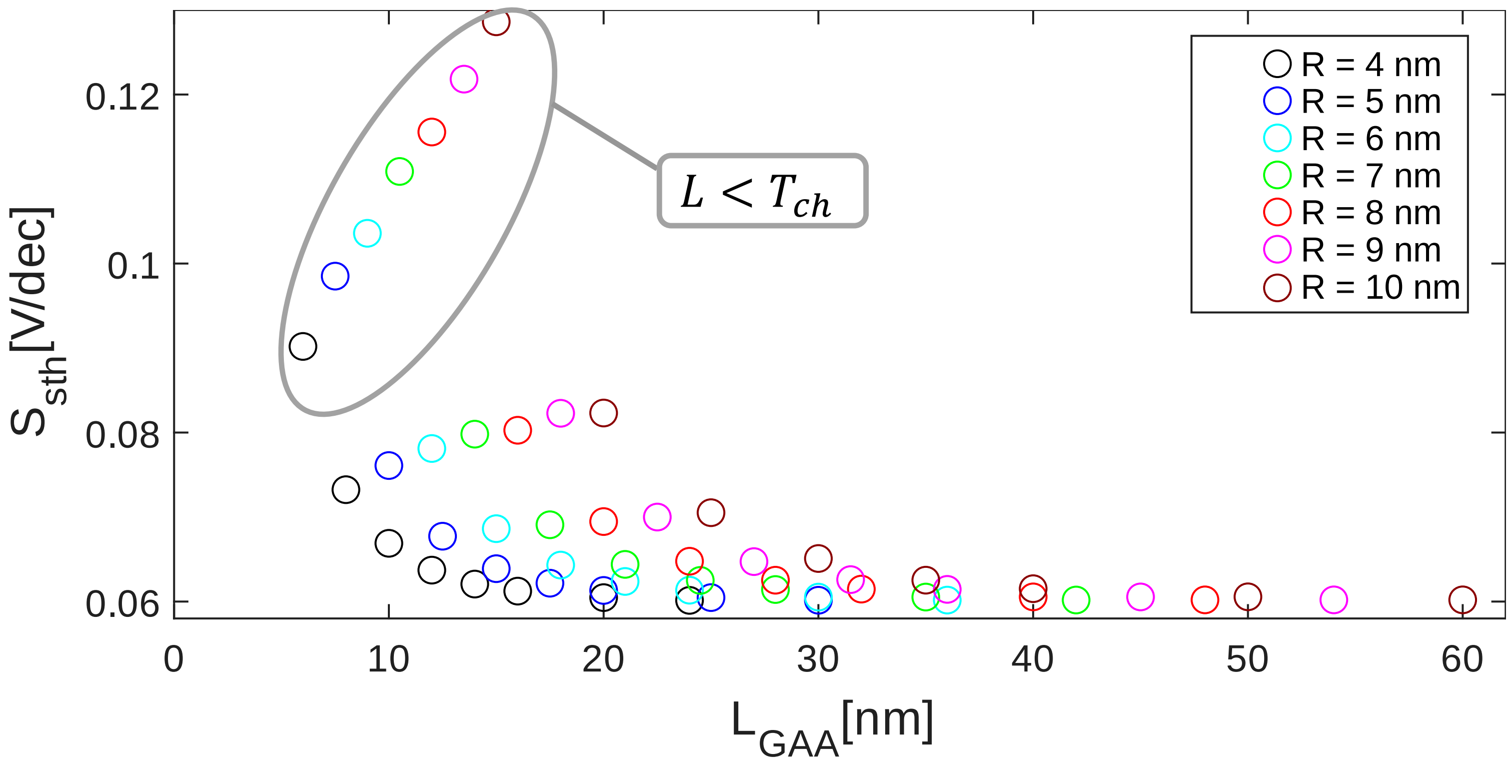
Subthreshold Swing S_{Sth} vs. channel length L_{GAA}



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o TCAD (GAA) ∗ TCAD (DG) +[1] Model +[2] Φ-TCAD & Model

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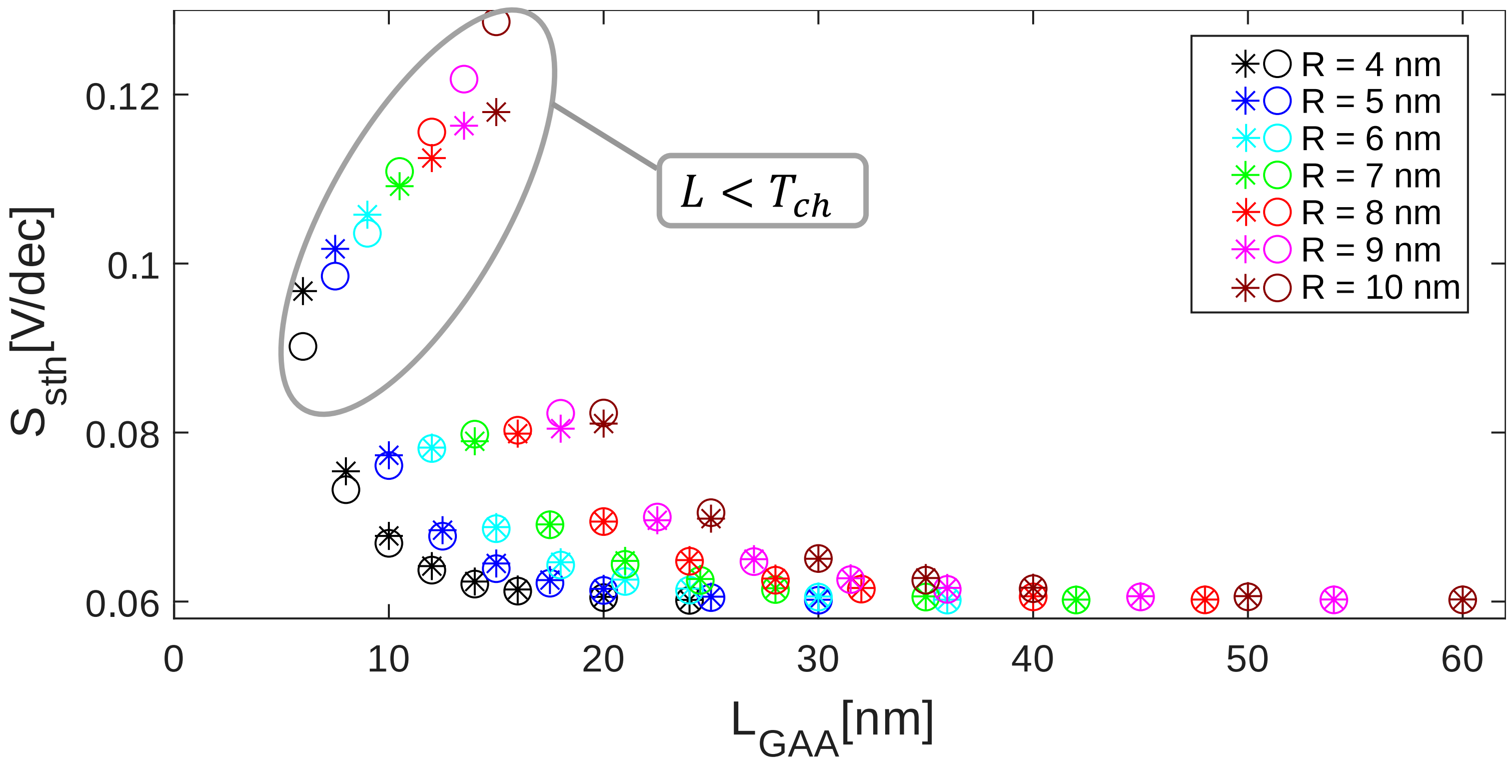

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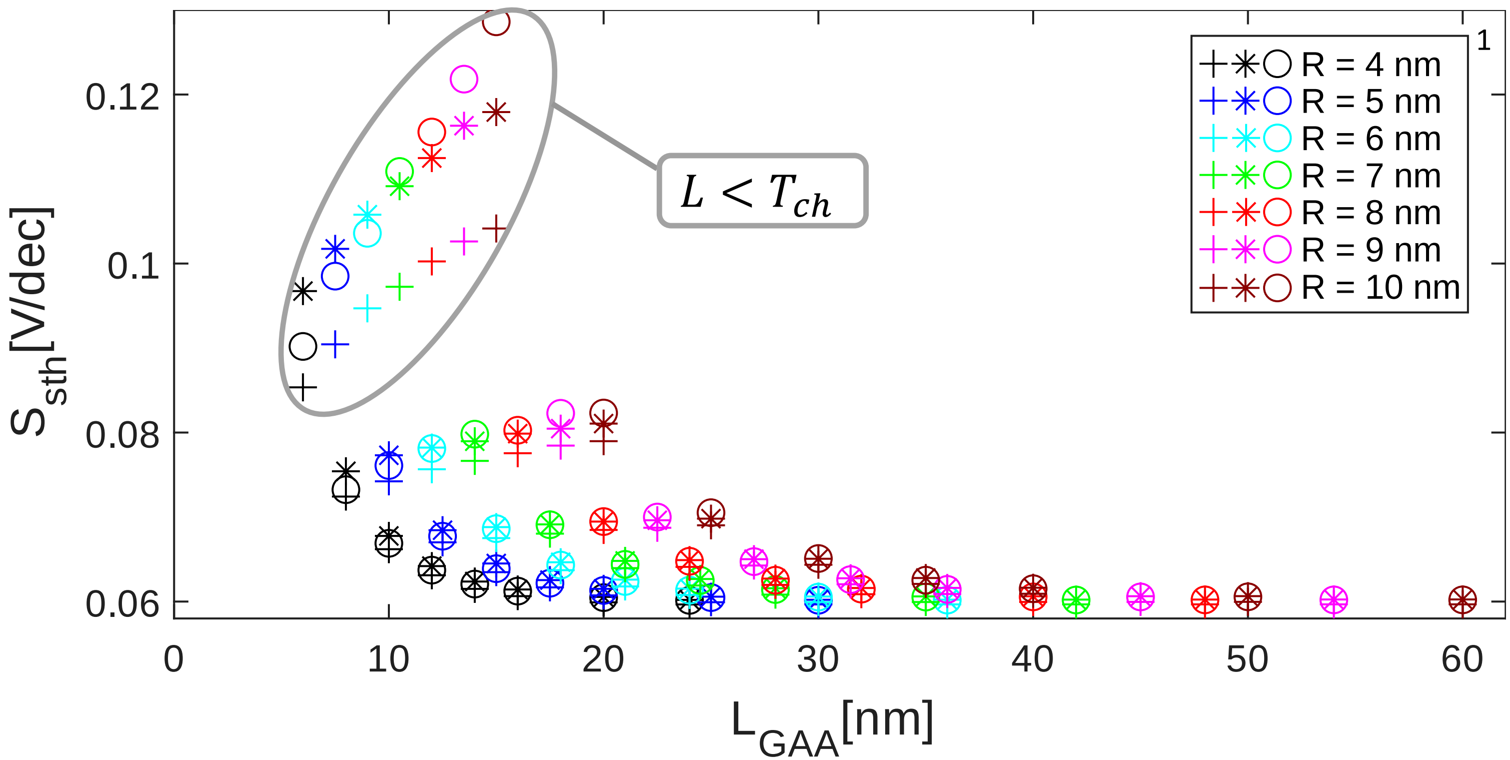

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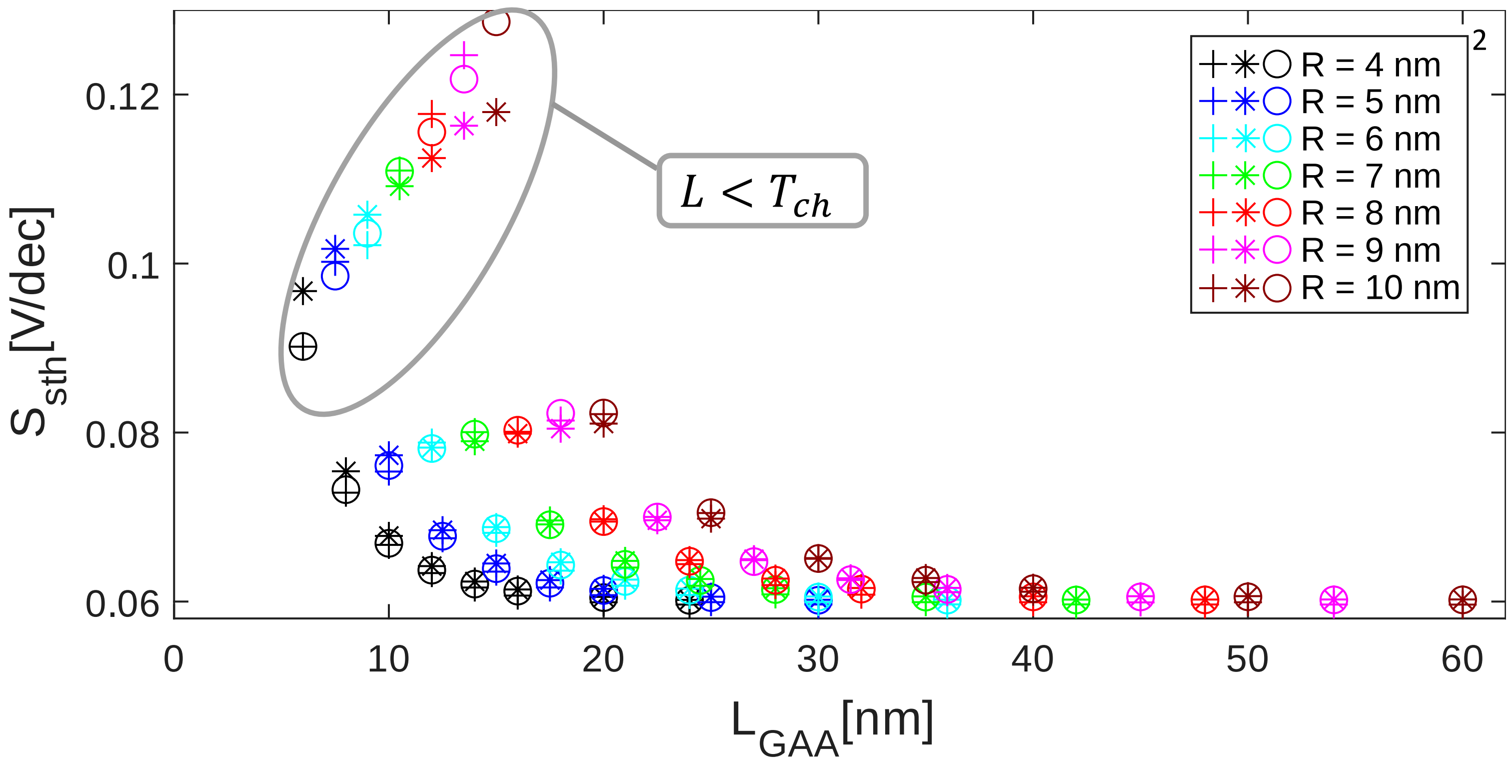

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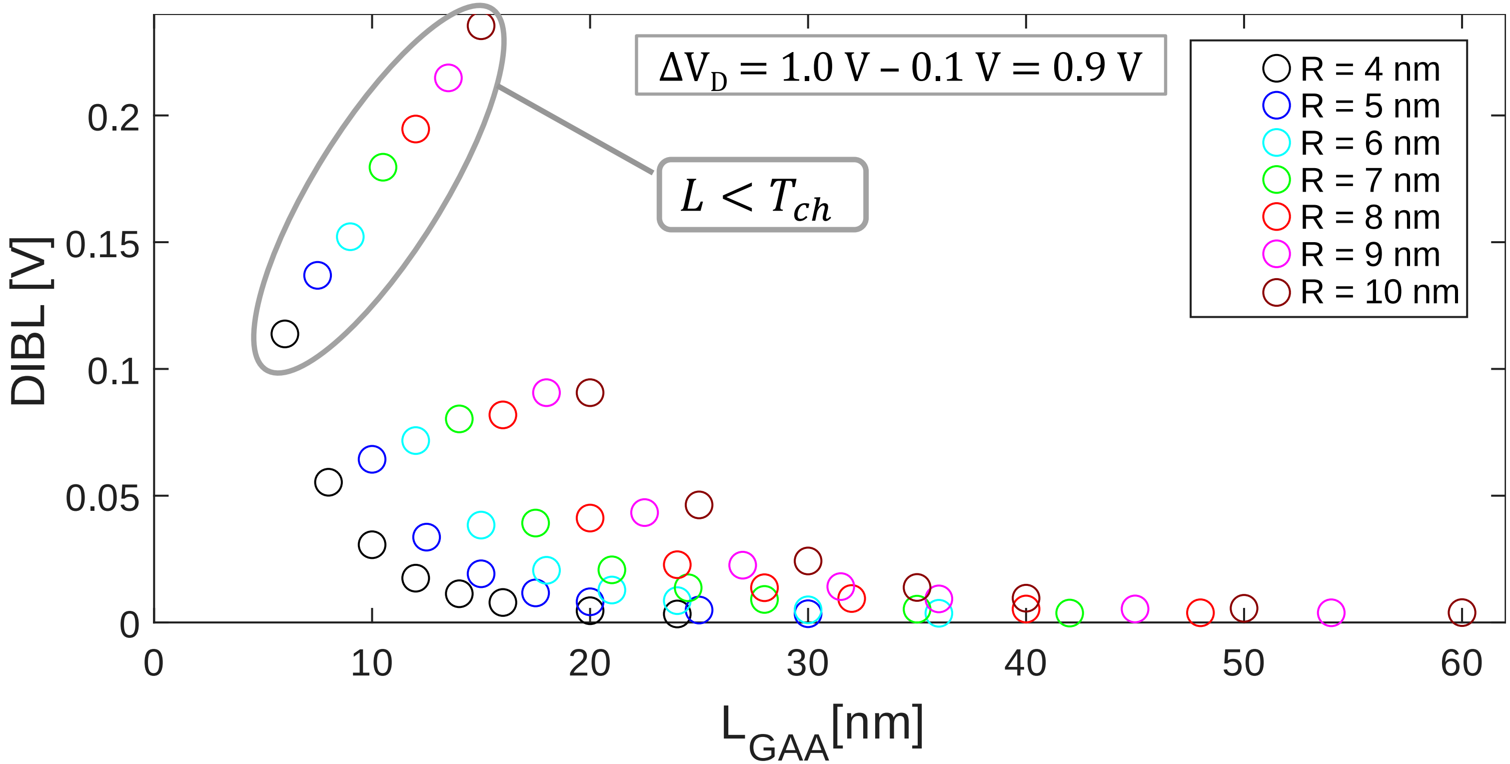
Drain-induced barrier lowering (DIBL) vs. channel length L_{GAA}



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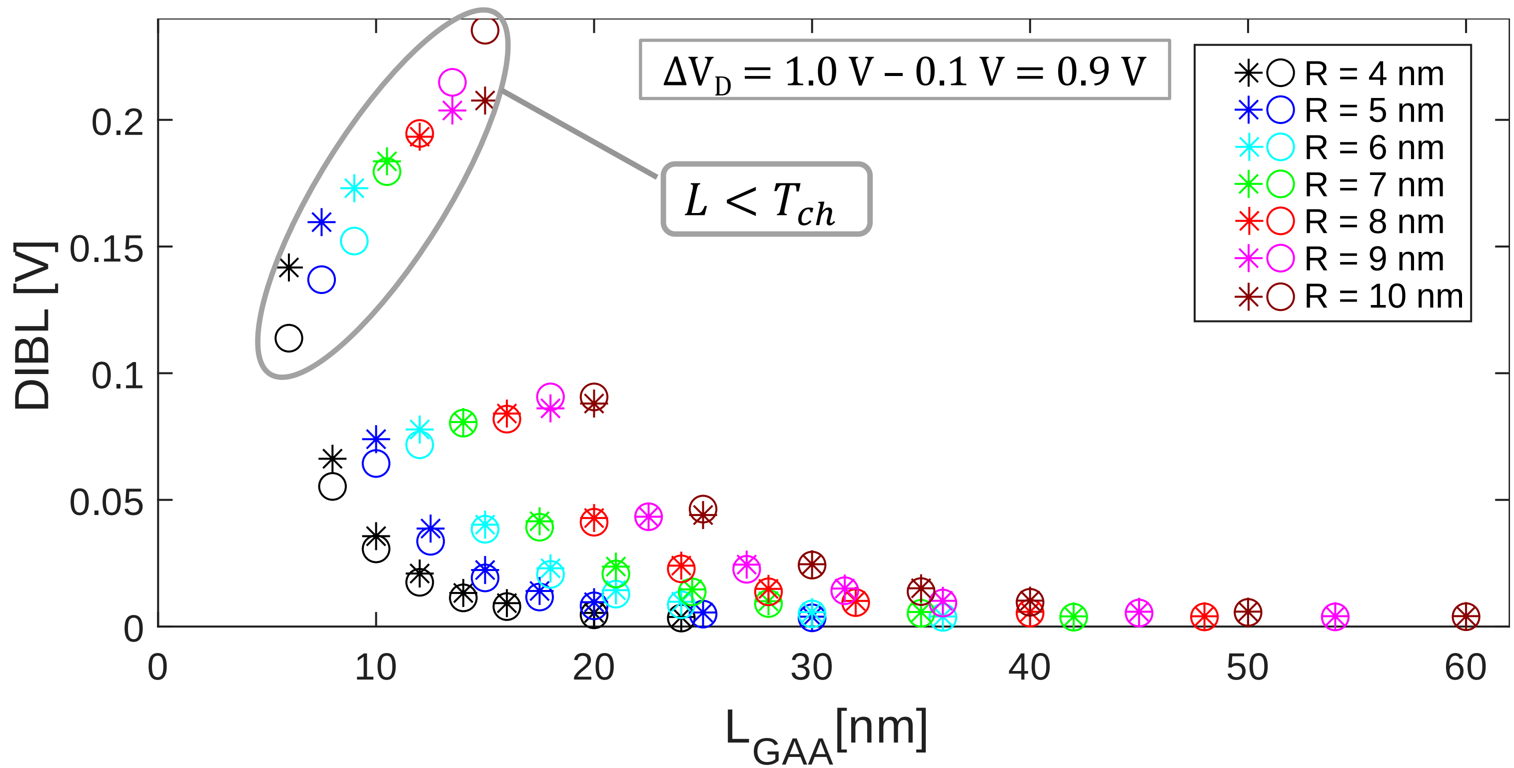

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o TCAD (GAA) ∗ TCAD (DG) $+^1$ Model $+^2$ Φ-TCAD & Model

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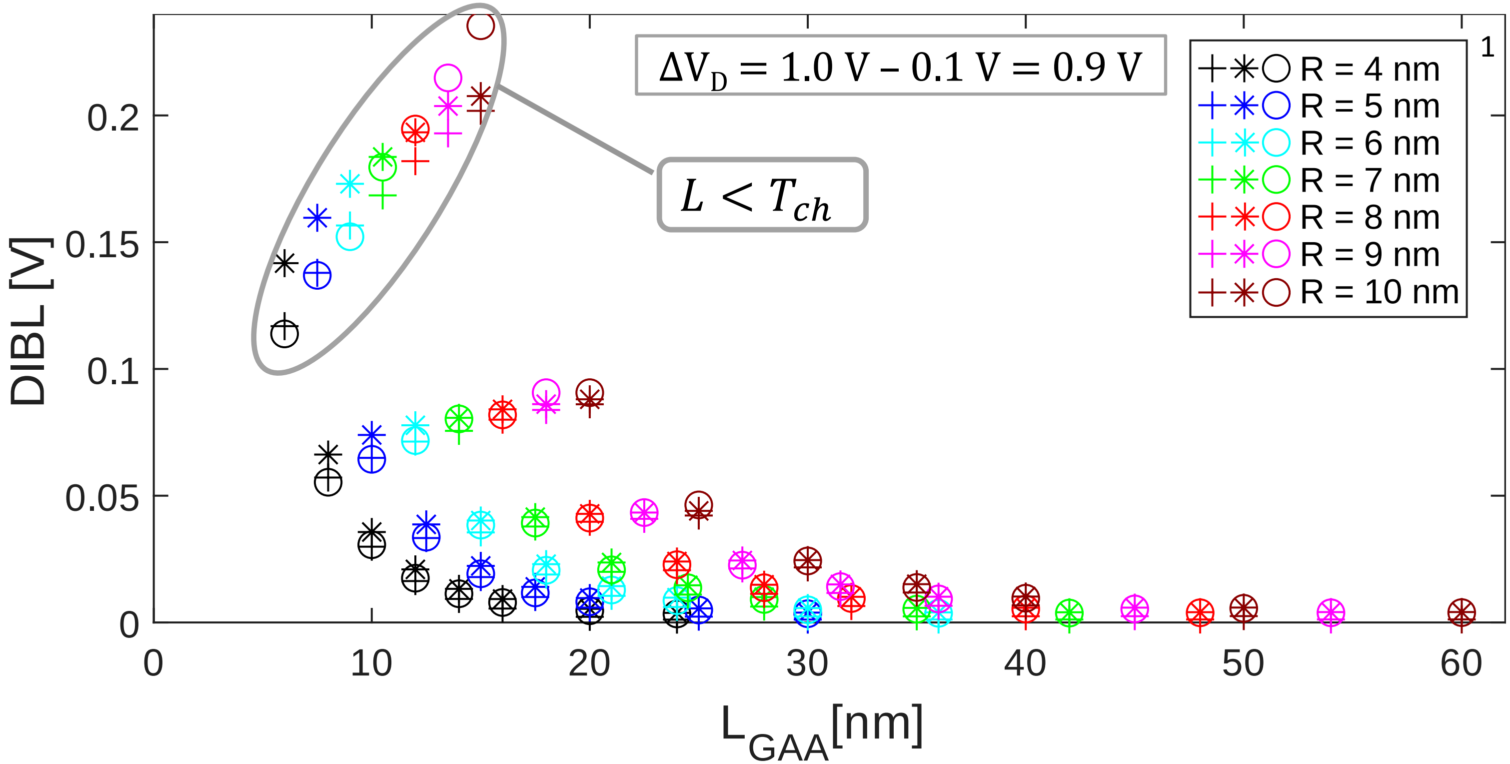

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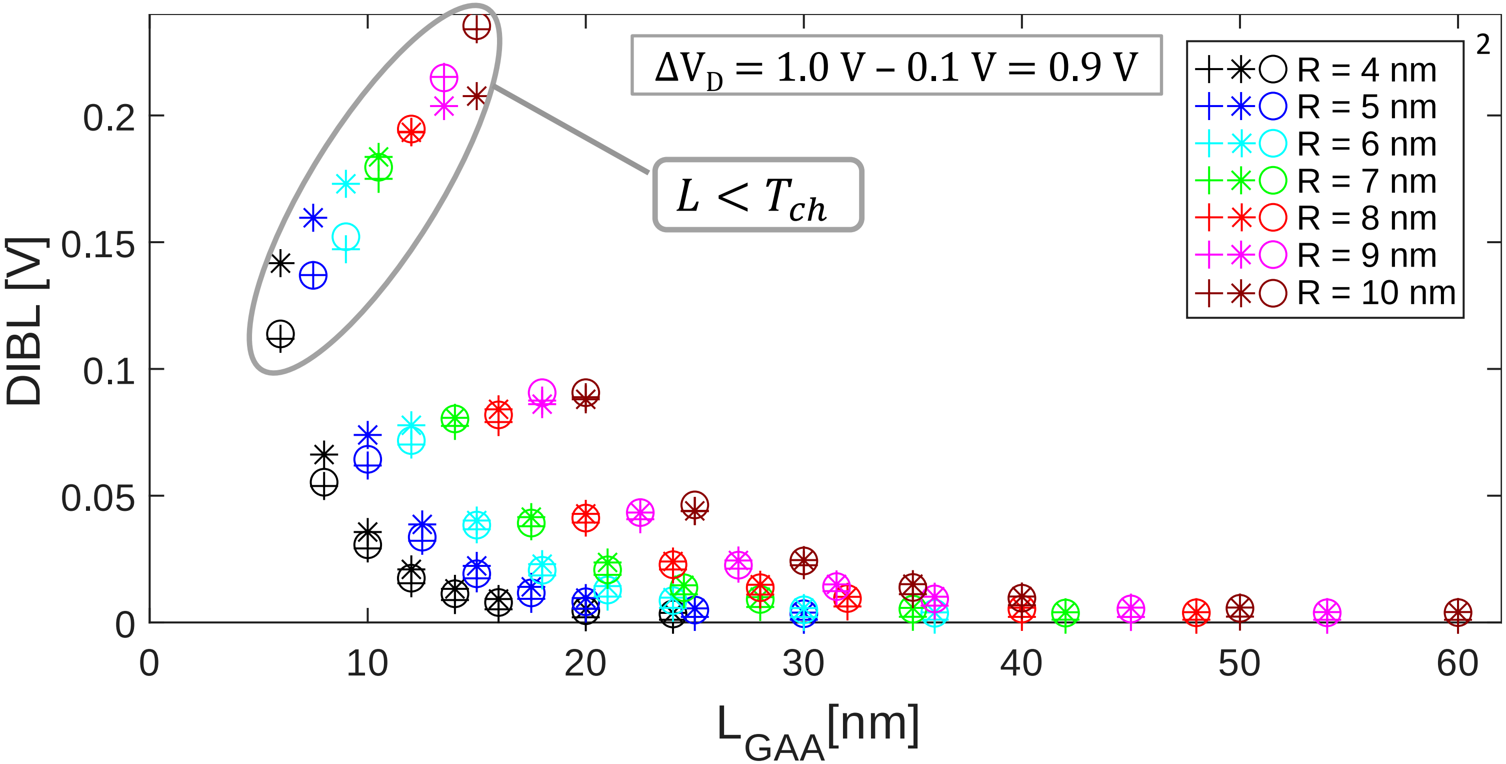

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4. Conclusion

- The equivalent capacitance concept is presented to capture short channel GAA MOSFET electrostatic & behavior by DG MOSFET.
- It is shown that the method is working properly for subthreshold region in intrinsic and lightly doped channel.
- The center and surface potential (ϕ_C & ϕ_S) need different equivalent values for the channel length.
- In subthreshold region where the leakage current mainly flows in the center, not only ϕ_C but also ϕ_S has significant influence on the electrostatic and characteristics.
- Outlook: The method is under development for above threshold short channel devices.