Analytical Modeling Framework for Short-Channel DG and GAA MOSFETs

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Silicon-based Nanodevices

Overview

Objectives:

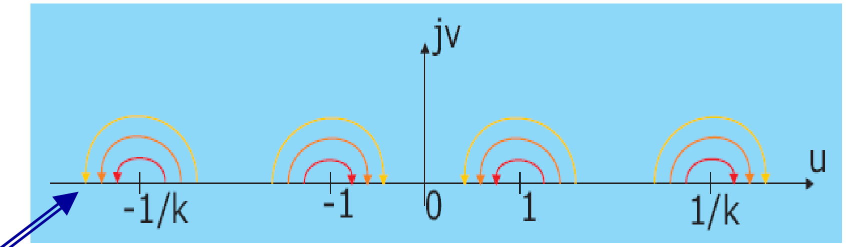
- Establish *framework for precise modeling* of short-channel nanoscale MOSFETs
- Establish *compact model expressions* with a minimal parameter set determined from the framework

Procedure:

- ***Capacitive inter-electrode effects***
  - In *subthreshold*, find analytical 2D solution for DG potential distribution and drain current
  - Use DG solution to obtain GAA solution with high precision
- ***Near threshold***
  - Apply Poisson's equations, boundary conditions, and modeling expressions for calculating the potential distribution
  - Determine *self-consistently* the total *potential distribution* and the *drain current* by including electrostatic effects from electrons
- **Strong inversion**
  - Use long-channel approximation

DG modeling details – subthreshold

- Include gate oxide in extended device body: $t'_{ox} = t_{ox}\epsilon_{ox}/\epsilon_{Si}$
- Map DG MOSFET body into upper half plane of transformed (u,iv)-plane using ***conformal mapping*** (Schwartz-Christoffel transform).
- ***Subthreshold***: Solve *Laplace's equation* in (u,iv)-plane (low-doped body)
  → 2D potential distribution for capacitive coupling. Map back to (x,y)-plane

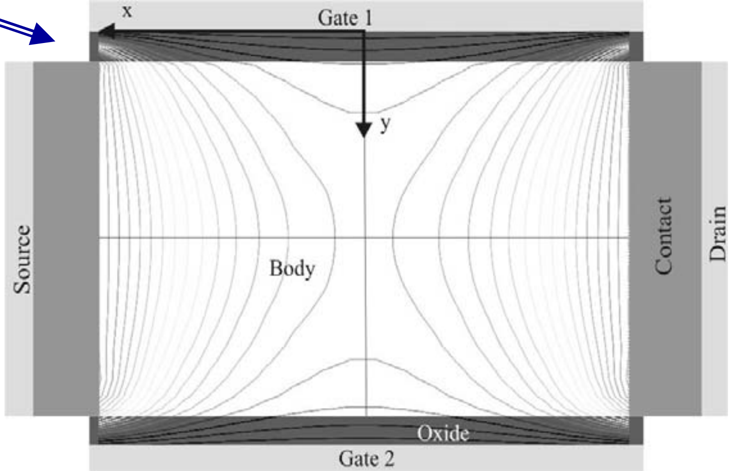


Schwartz-Christoffel transformation

$$z = x + iy = \frac{L}{2}\frac{F(k, u+iv)}{K(k)}$$

$$F(k,w) = \int_0^w \frac{dw'}{\sqrt{(1-w'^2)(1-k^2w'^2)}}, \qquad K(k) = F(k,1)$$

$$\varphi(u,v) = \frac{v}{\pi}\int_{-\infty}^{\infty}\frac{\varphi(u')}{(u'-u)^2+v^2}du' = \frac{1}{\pi}\left\{\begin{aligned} &(V_{GS2}-V_{FB})\left[\pi - \tan^{-1}\left(\frac{1-ku}{kv}\right) - \tan^{-1}\left(\frac{1+ku}{kv}\right)\right] \\ &+(V_{GS1}-V_{FB})\left[\tan^{-1}\left(\frac{1-u}{v}\right) + \tan^{-1}\left(\frac{1+u}{v}\right)\right] \\ &+V_{bi}\left[\tan^{-1}\left(\frac{1-ku}{kv}\right) - \tan^{-1}\left(\frac{1-u}{v}\right)\right] \\ &+(V_{bi}+V_{DS})\left[\tan^{-1}\left(\frac{1+ku}{kv}\right) - \tan^{-1}\left(\frac{1+u}{v}\right)\right] \end{aligned}\right\}$$



GAA modeling details – subthreshold

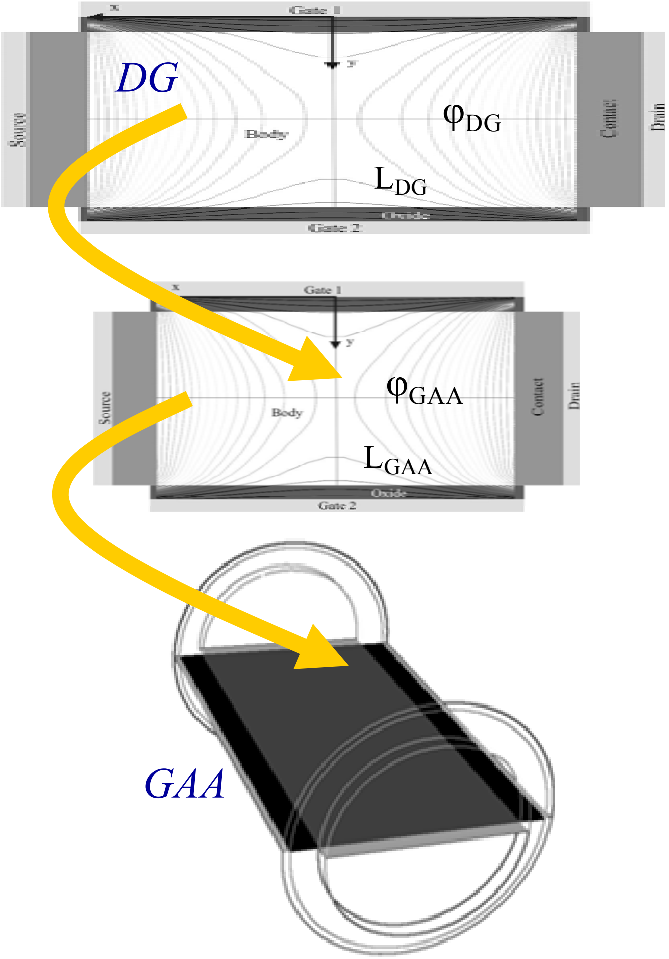
- Observe structural similarities with 2D DG MOSFET potential
- Major difference: Field penetration into body from S and D electrodes, determined by characteristic lengths:

$$\lambda_{DG} = \sqrt{\frac{\varepsilon_{si}}{2\varepsilon_{ox}}\left(1+\frac{\varepsilon_{ox}t_{si}}{4\varepsilon_{si}t_{ox}}\right)t_{si}t_{ox}}\ ,\ \lambda_{GAA} = r_{si}\sqrt{\frac{1}{4}+\frac{\varepsilon_{si}}{2\varepsilon_{ox}}\ln\left(1+\frac{t_{ox}}{r_{si}}\right)}$$

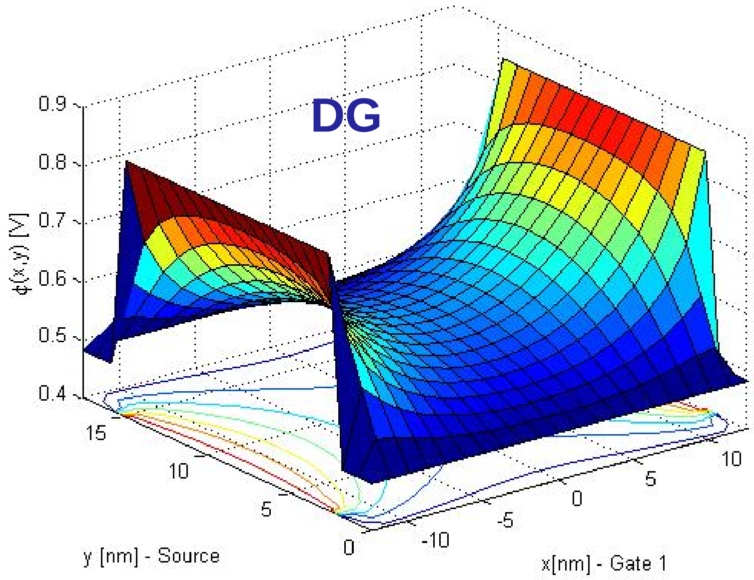
- Map φ_{DG} from device with length

$$L_{DG} = \frac{\lambda_{DG}}{\lambda_{GAA}} L_{GAA}$$

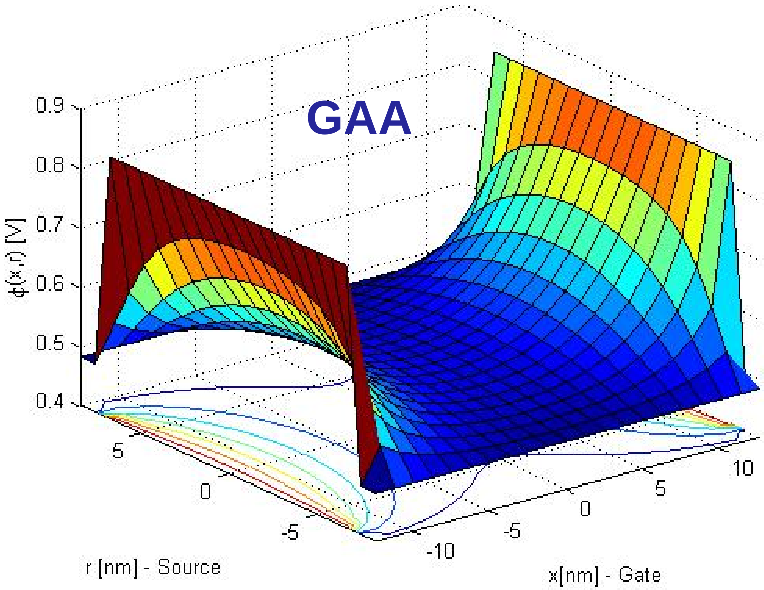
into GAA MOSFET body cross-section with length L_{GAA}



Subthreshold potential distributions



$V_{GS} = V_{DS} = 0$ V

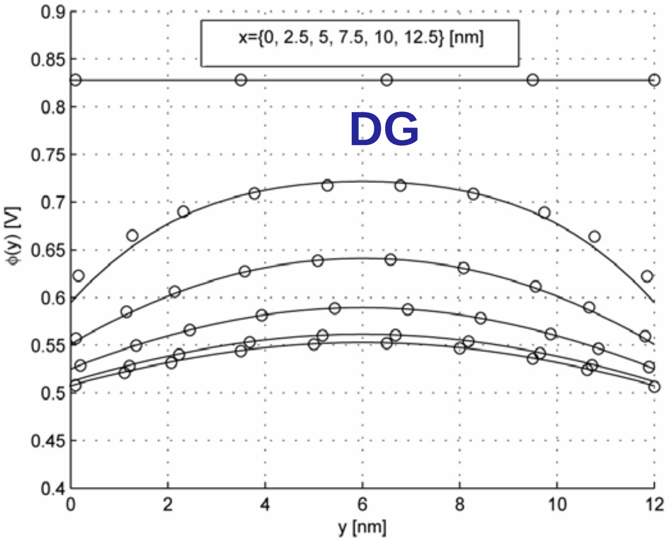


$V_{GS} = V_{DS} = 0$ V

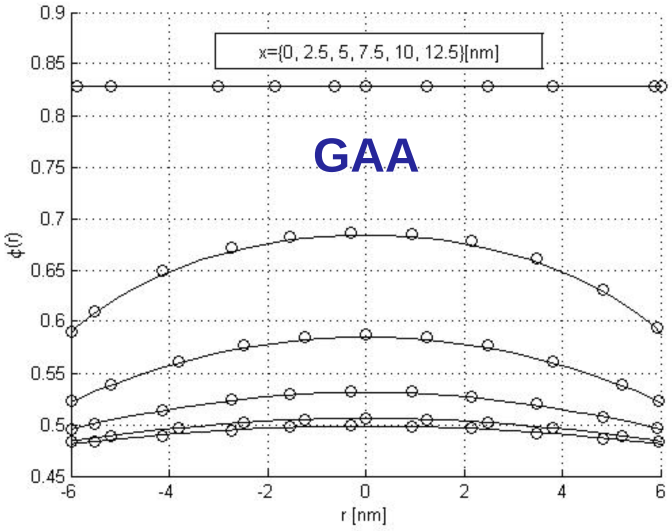
Devices considered: *n*-channel DG and GAA MOSFETs

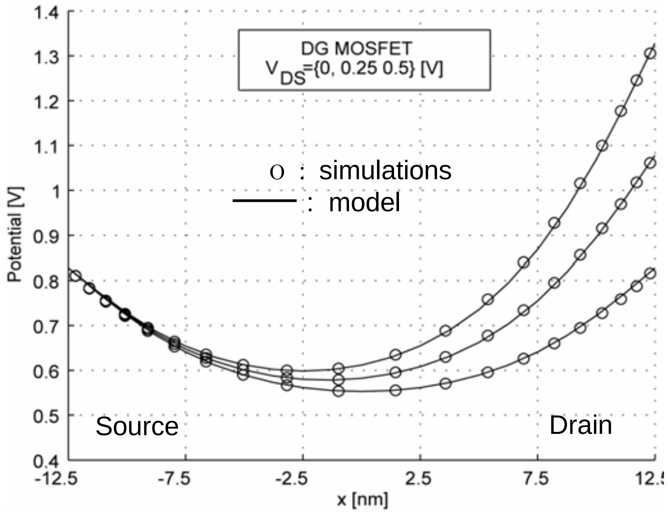
Specifics: $L = 25$ nm, $t_{si} = 12$ nm, $t_{ox} = 1.6$ nm, $\varepsilon_{ox} = 7$, body doping $N_d = 10^{15}$ cm^{-3}, midgap gate metal $\varphi_{msg} = 4.53$ eV, 'metallic' source/drain contacts $\varphi_{msc} = 4.17$ eV (as for n+ Si)

Subthreshold – verification

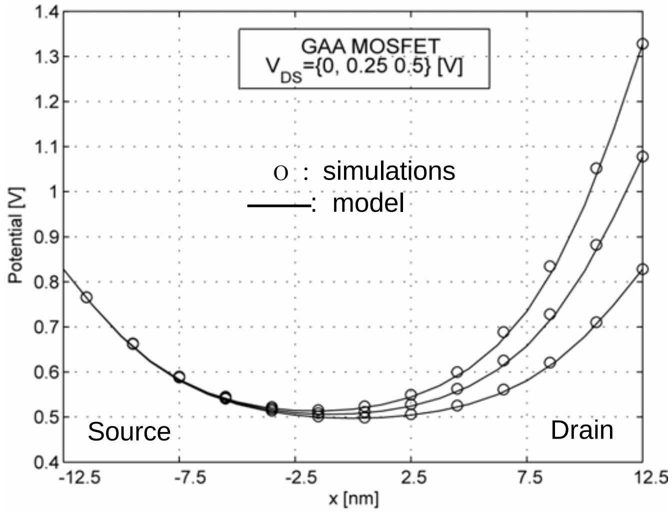


Subthreshold gate-to-gate pot. Profiles $V_{GS}=V_{DS}=0$ V

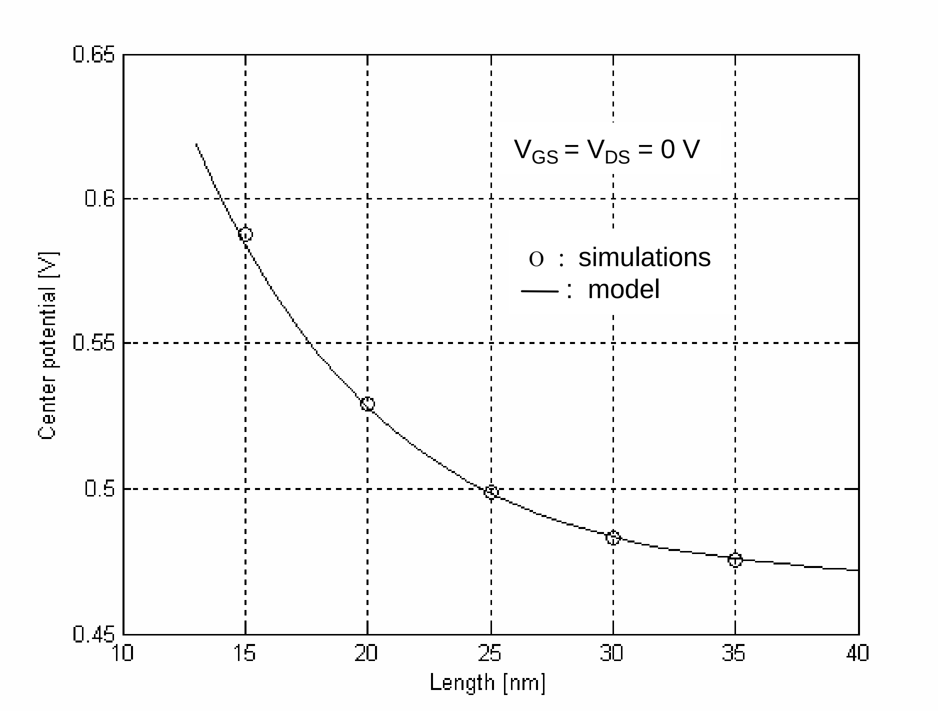




Subthreshold source-to-drain pot. Profiles V_{GS} = 0 V



Scaling – center potential of GAA



Scaling of center potential with
gate length in subthreshold

Near threshold – self-consistency

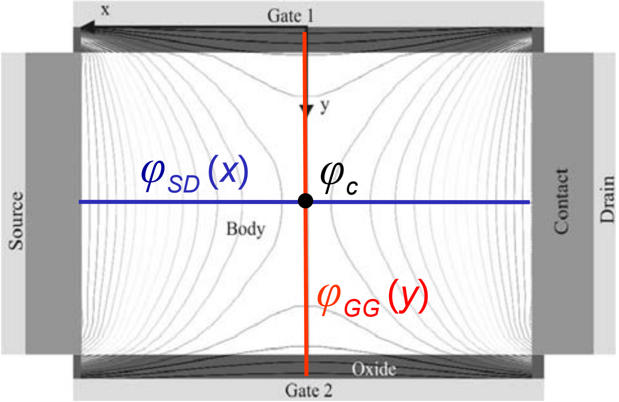
Procedure

Initiation

- Estimate center potential φ_c from long-channel limit.
- Approximate $\varphi_{GG}(y)$ along G-G symmetry axis using long-channel limit.
- Establish modeling expression $\varphi_{SD}(x)$ along S-D symmetry axis using boundary conditions near S and D drain and from center point
- From $\varphi_{GG}(y)$ and $\varphi_{SD}(x)$, establish approximate G-G distributions at different cut-lines.
- For finite V_{DS}, estimate a quasi-Fermi potential at the device center (for example, $V_{Fc} = V_{DS}/2$)

Processing

- Calculate current and update V_{Fc}
- Estimate $\varphi''_{SD}(0)$ from $\varphi_{SD}(x)$ and apply to Poisson's equation to update φ_c.
- Update $\varphi_{GG}(y)$ and $\varphi_{DS}(x)$
- Repeat until satisfactory accuracy is obtained (typically 3 iterations)



Threshold voltage:

Defined as V_{GS} for which

$$\varphi_{GG}(y) = \text{const} = V_{FB}$$

when V_{DS} = 0 V. Find for our devices:

V_T(DG) = 0.25 V
V_T(GAA) = 0.24 V

Strong inversion

Gate-to-gate symmetry line

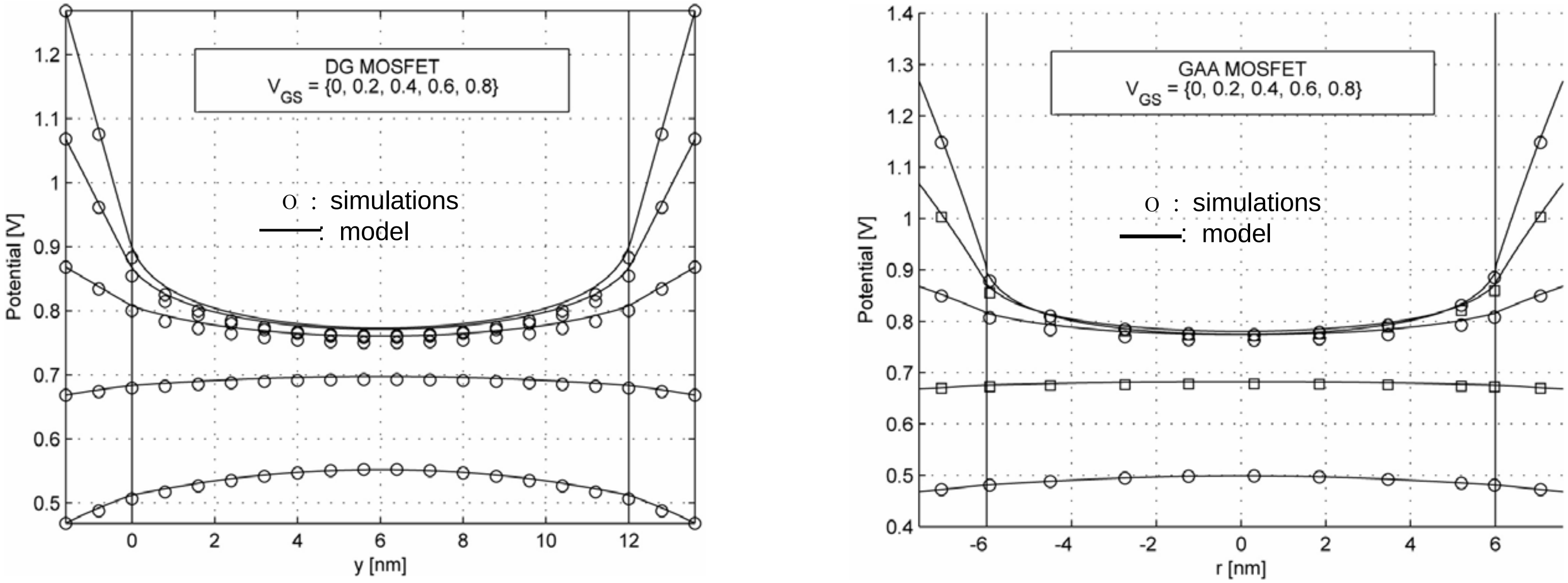
For DG MOSFET, use long-channel potential $\varphi_{GG}(y)$ from 1D Poisson's equation (Taur 2001), adjusted to include effects of body doping:

$$\boxed{\varphi_{GG}(y) = \varphi_c - 2V_{th} \ln\left[\cos\left(\sqrt{\frac{qn_i}{2\varepsilon_s V_{th}}}\exp\left(\frac{\varphi_c - \varphi_b}{2V_{th}}\right)(y - t'_{ox} - t_{Si}/2)\right)\right]}$$

Correspondingly for GAA MOSFET (Iniguez 2005).

Note: Inter-electrode capacive effects screened by adaption of the electron distribution.

$\varphi_{GG}(y)$ along G-G symmetry axis



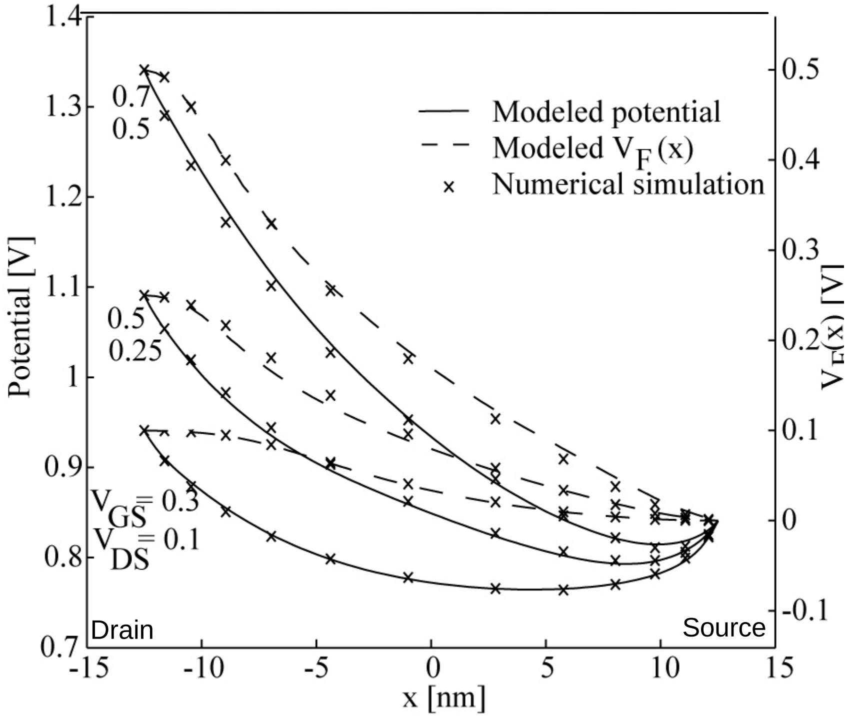
DG

GAA

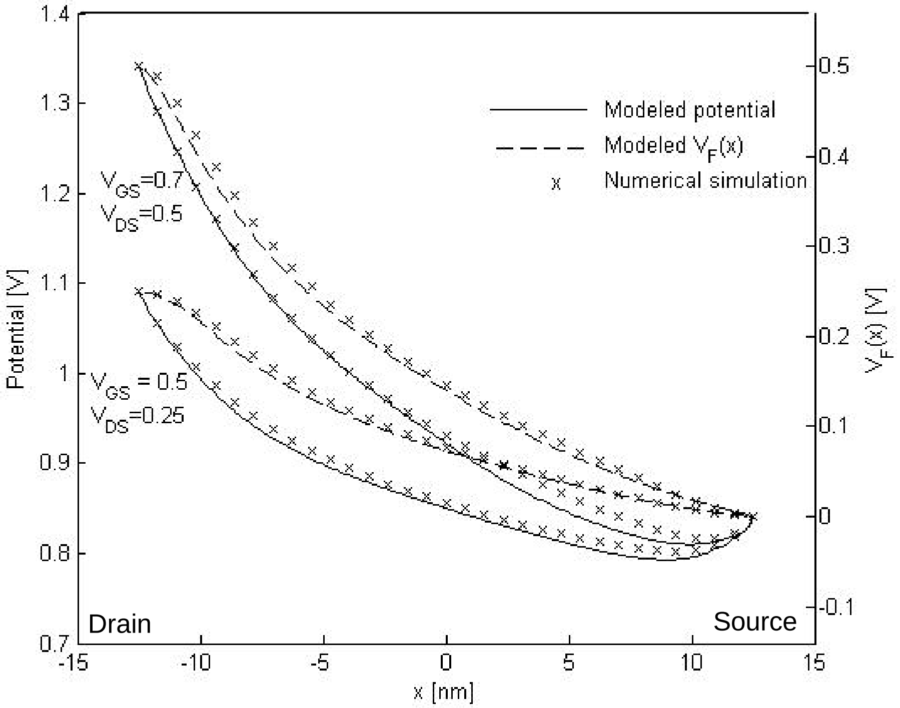
Central gate-to-gate pot. profiles vs. V_{GS} for V_{DS} = 0 V

$\varphi_{DS}(x), V_F(x)$ along D-S symmetry axis

DG

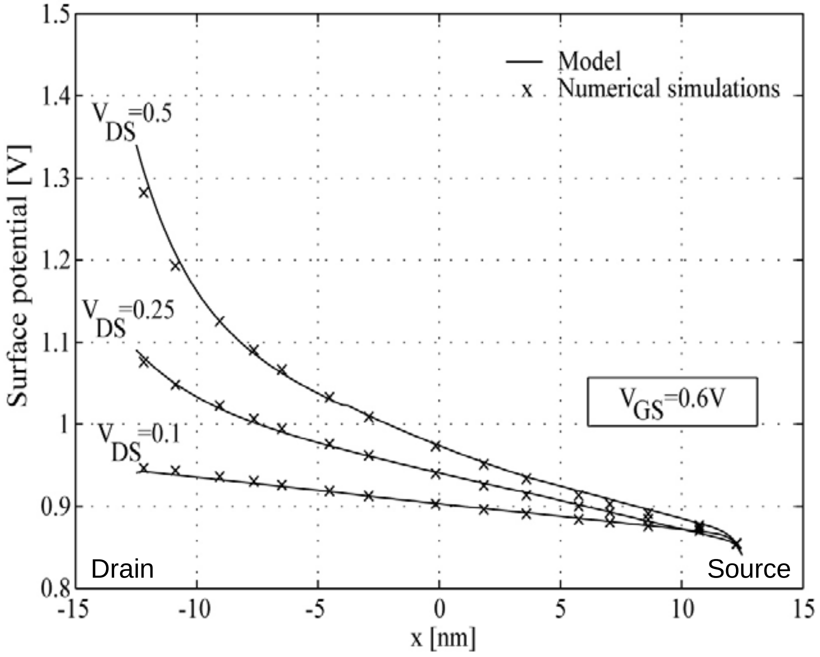


GAA

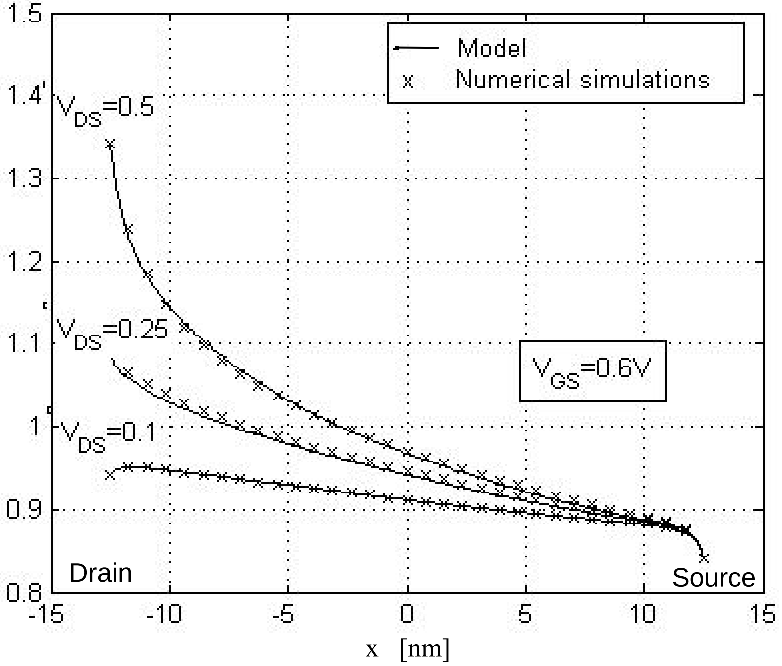


Interface potential in strong inversion

DG



GAA



Drain current modeling

Drift-diffusion transport:

Use electron density derived self-consistently in:

$$\boxed{I_{DD} = -qW\mu_n n_s(x)\frac{dV_F(x)}{dx} = \frac{qW\mu_n V_{th}\left(1-e^{-V_{DS}/V_{th}}\right)}{\int_0^L \frac{dx}{n_{so}(x)}}}$$

$n_{so}(x)$: surface concentration of electrons in all cross-sections from source to drain using $V_F(x)$ = const. = V_{FS}.

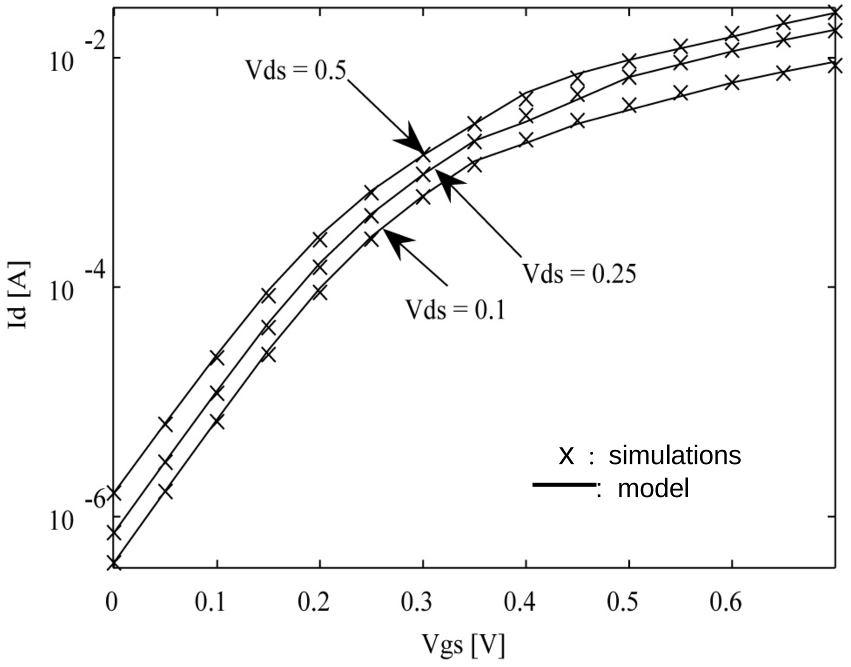
Ballistic transport (*not considered here*):

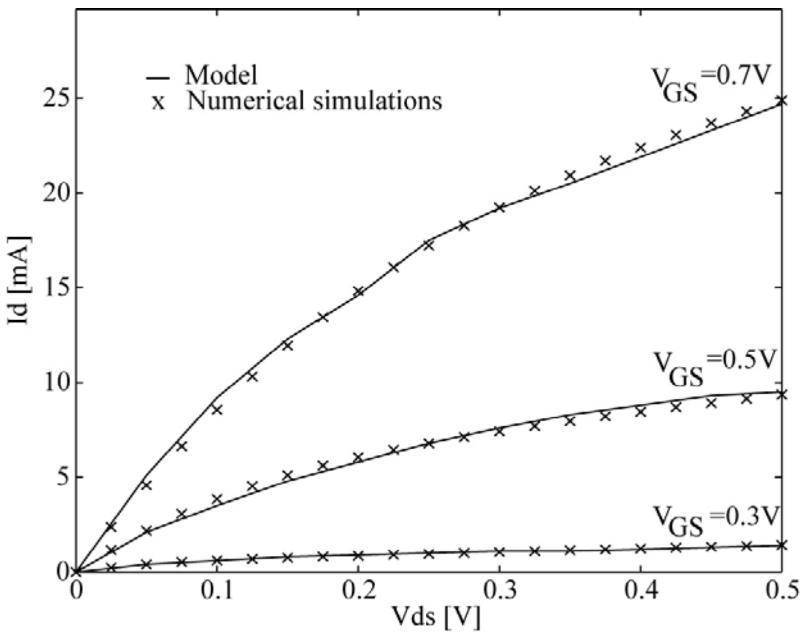
- Current consists of free-flight electrons with sufficient energy to fly over barrier
- Electrons ’filtered’ through available quantum states at barrier position
- Current limited by ability of source and drain to supply high-energy carriers fast enough

Natori formalism (1994, 2002):

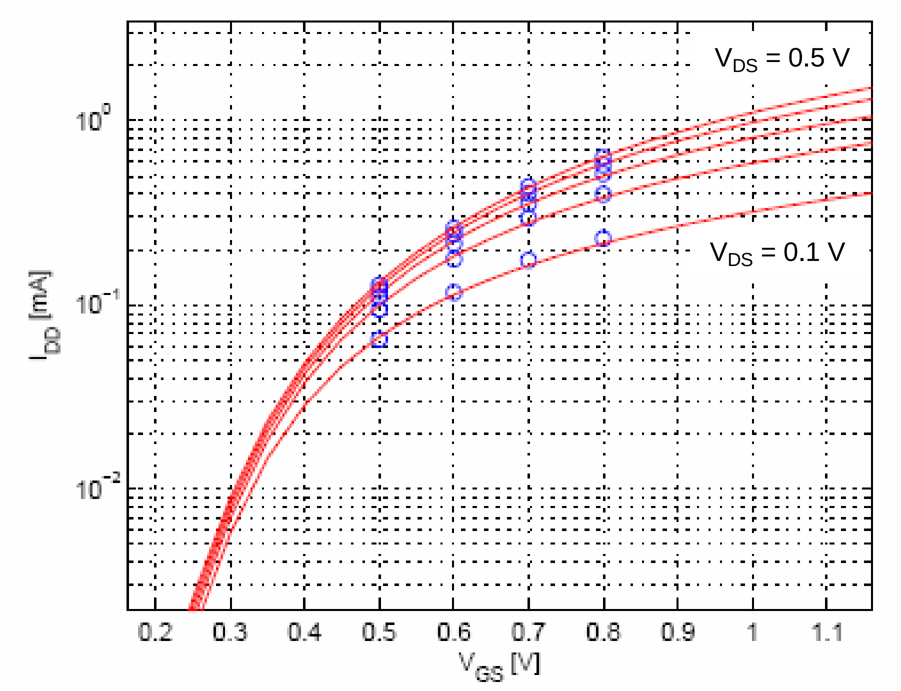
$$I_{BT} = q(F^{+}\text{-}F^{-}) \quad \text{where} \quad F^{\pm} = \frac{(2k_BT)^{3/2}}{\pi^2\hbar^2}\sum_{valleys}\sum_{j}\sqrt{m_i}\,F_{1/2}\left(\frac{E_{Fs}-E_{ij}-qV^{\pm}}{k_BT}\right)$$

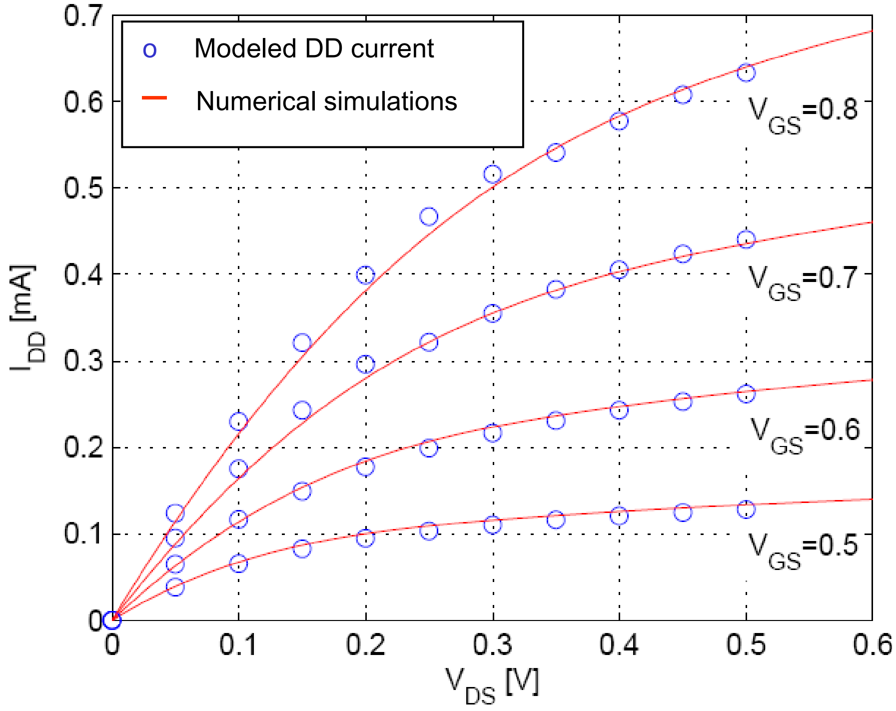
Drain current modeling – DG MOSFET





Drain current modeling – GAA MOSFET





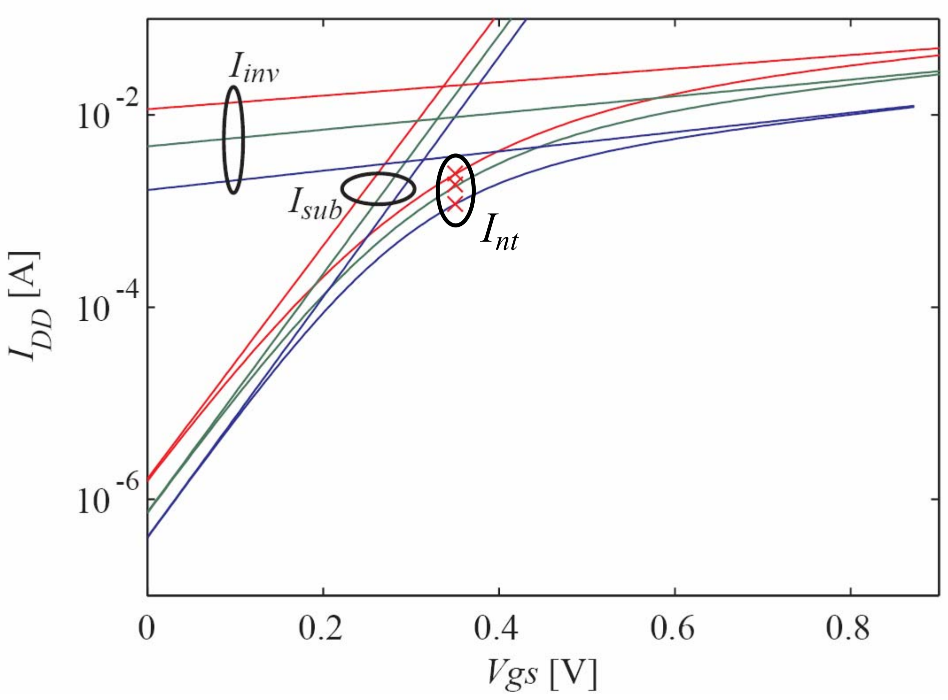
Compact modeling of drain current – example

’Generic’ modeling expression

$$I_{DD} = 10\ \hat{}\ \left[\frac{\log(I_{sub})}{\left[1 + \left(\frac{\log(I_{sub})}{\log(I_{inv})}\right)^{m}\right]^{1/m}} \right]$$

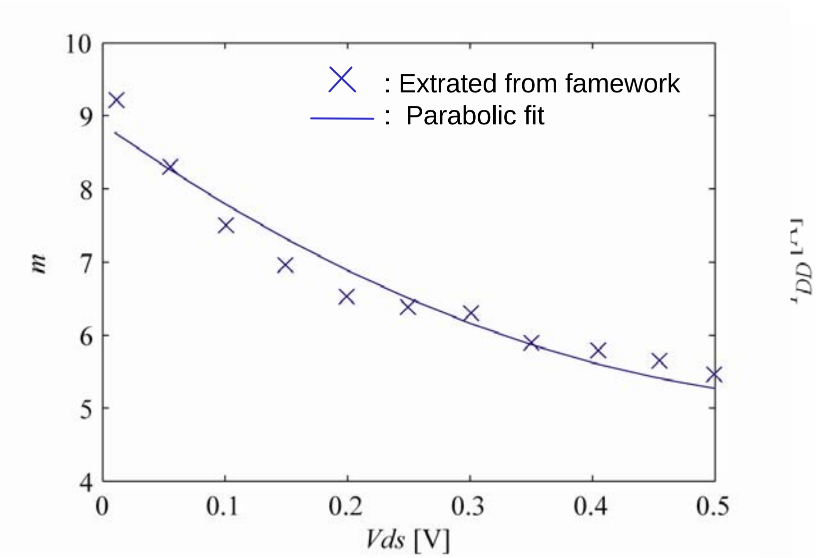
Procedure:

- Use limiting forms of I_{DD} in subthreshold (I_{sub}) and strong invertion (I_{inv})
- Calculate I_{DD} near threshold (I_{nt}) from modeling framework
- Use I_{nt} versus V_{GS} to determine the shape parameter $m(V_{GS})$



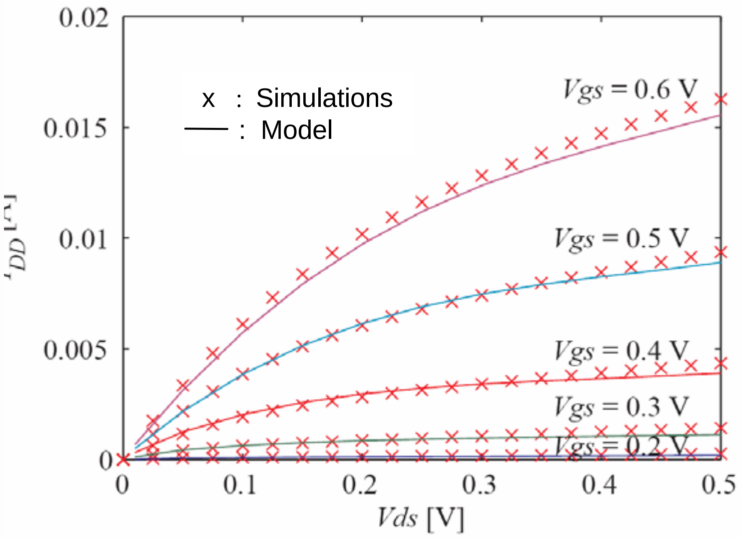
Compact modeling of drain current
– DG MOSFET

Extraction of parameter m



Use least-squares fit of a second degree polynomial (3 parameters)

Resulting $I_{DD} – V_{DS}$ characteristics



Note: A better precision in *m* (more parameters) would give a better fit to the numerical modeling

Summary

Precise *modeling framework* established for short-channel, nanoscale DG and GAA MOSFETs featuring:

- *Full range of applied bias voltages*
- *Self-consistency*
- *Full potential and QFP distributions*
- *Drift-diffusion drain current*
- *No adjustable parameters*

Compact model expressions established with a minimal parameter set extractable from the framework

Models verified by numerical simulations (ATLAS/Silvaco)