PSP-based scalable compact FinFET model

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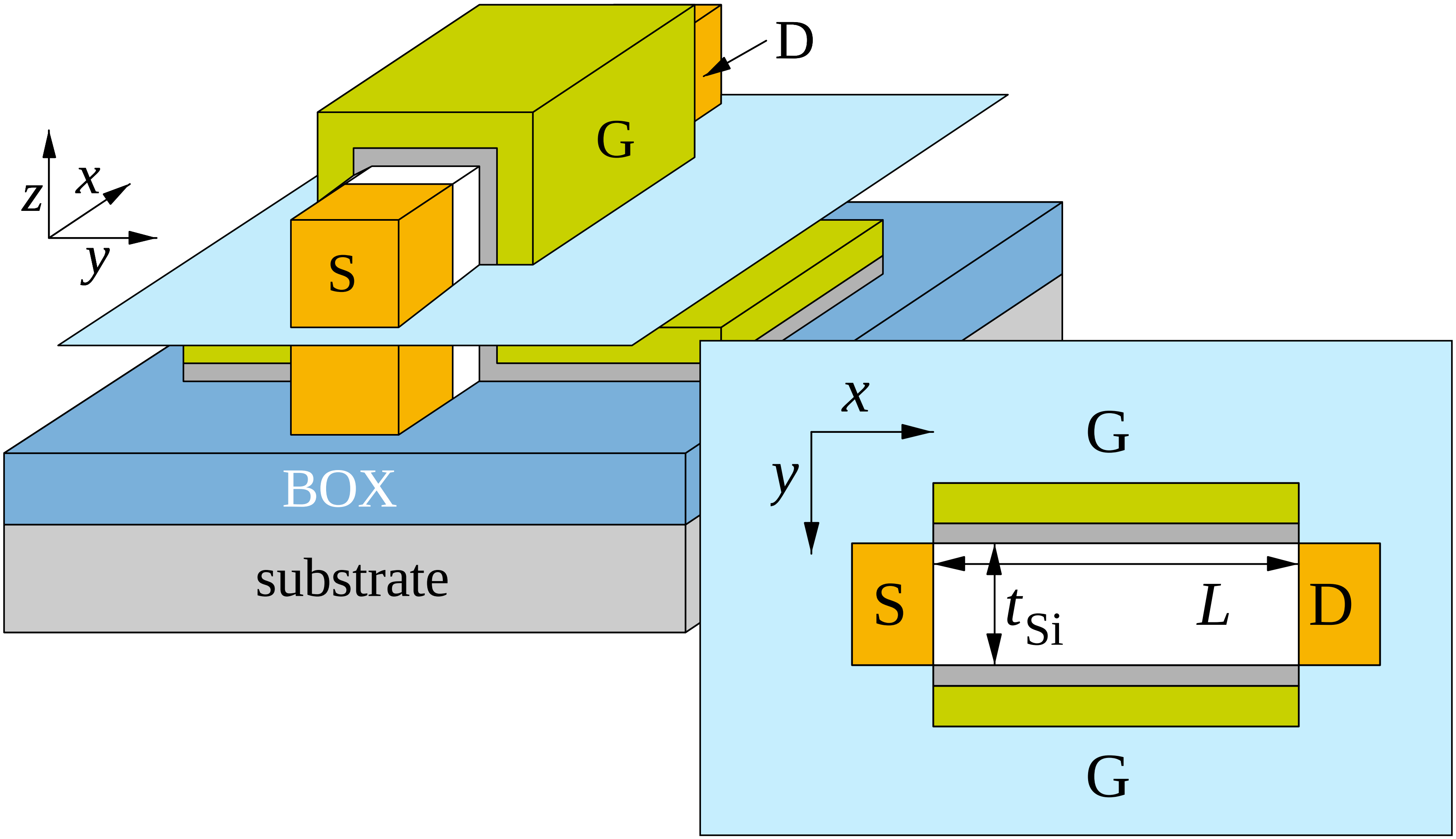
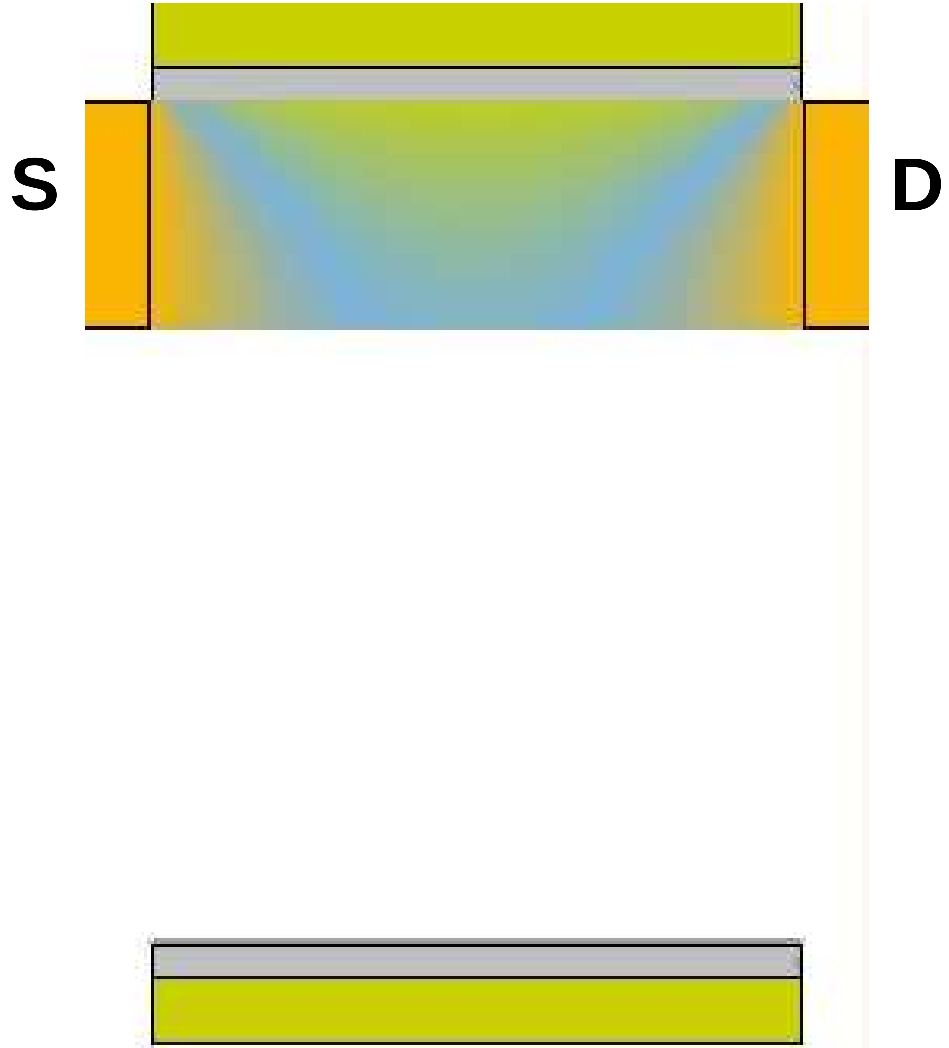
introduction

- FinFETs are candidates to replace bulk MOSFETs
  - good control of short channel effects
- compact model development
  - compact model required for circuit design
  - no (public domain) FinFET models available
- extending the PSP model-family
  - bulk CMOS
  - PD-SOI
  - FD-SOI
  - FinFET
  - …
- FinFET is fully depleted device
  - fundamentally different electrostatics
  - touches the heart of a compact model

device



channel control in FinFET



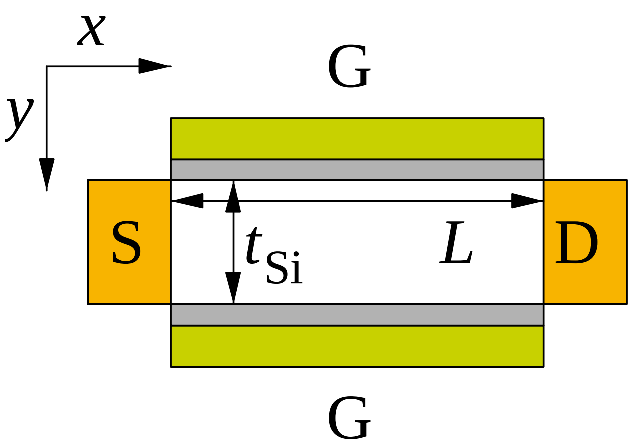
(animation)

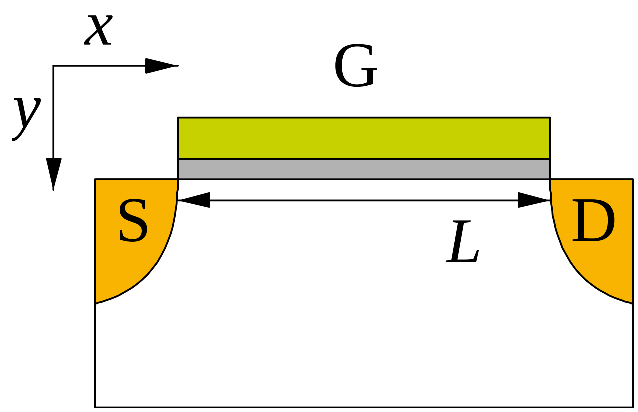
outline

- introduction
- core model
  - surface potential equation & its solution
  - currents and charges
  - new model
- geometry scaling
  - parameter extraction
  - results
- conclusion

core model

surface potential equation (i)





- 2D Poisson equation $-\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}\right)=\frac{\rho}{\varepsilon}$
- gradual channel approximation
- 1D Poisson equation $-\frac{\partial^2\psi}{\partial y^2}=\frac{\rho}{\varepsilon}$
- charge density $\rho=-q\cdot N_A\cdot\left(1+e^{-q\cdot(V+\varphi_B)/k\cdot T}\cdot e^{q\cdot\psi/k\cdot T}-e^{-q\cdot\psi/k\cdot T}\right)$

doping electrons holes

surface potential equation (ii)

- normalize $$\frac{\partial^2 \psi}{\partial y^2} = f(\psi)$$ $$f(\psi) = (1 + e^{\psi - v} - e^{-\psi})/2$$
- integrate once $$(\psi')^2 - F(\psi) = \alpha$$

$$F(\psi) = 2\int f(\psi)d\psi = \psi + e^{-v}(e^{\psi} - 1) + (e^{-\psi} - 1)$$

α → integration constant

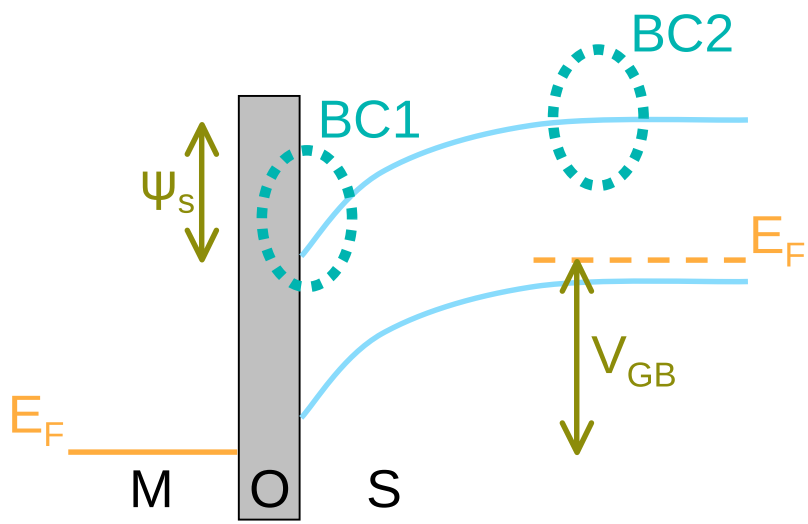
surface potential equation (iii) – bulk MOSFET

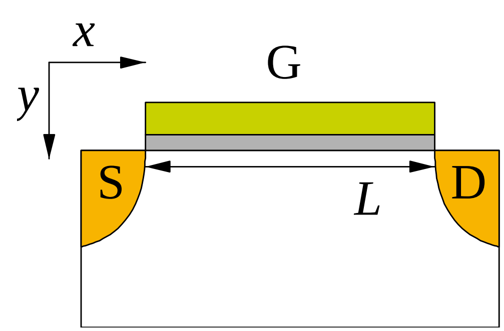
$$(\psi')^2 - F(\psi) = \alpha$$

- BC1: $\psi' = C_{ox}(\psi_s - V^*_{GB})$
- BC2: $\psi' = 0$
- α=0
- ψ_s can be solved from:

$$(\psi_s - V^*_{GB})^2 = F(\psi_s)$$

- note: ψ(y) is *not* yet known

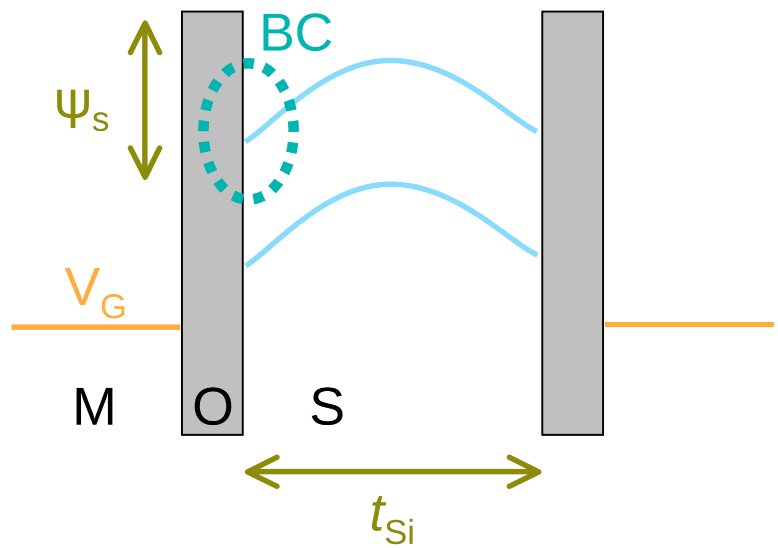




surface potential equation (iv) – FinFET

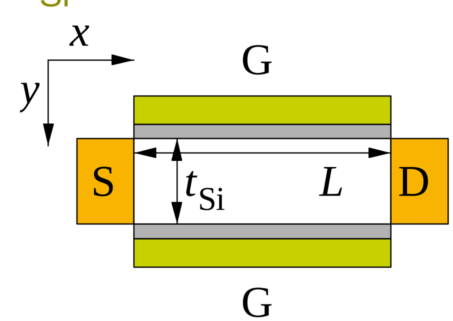
$$(\psi')^2 - F(\psi) = \alpha$$

- BC: $\psi' = C_{ox} \cdot (\psi_s - V_G^*)$



- ψ_s cannot yet be solved
- need second integration step

$$t_{Si} = \int_{\psi_{s,1}}^{\psi_{s,2}} \frac{d\psi}{\sqrt{F(\psi) + \alpha}}$$



- two equations (including integral) to be solved ☹

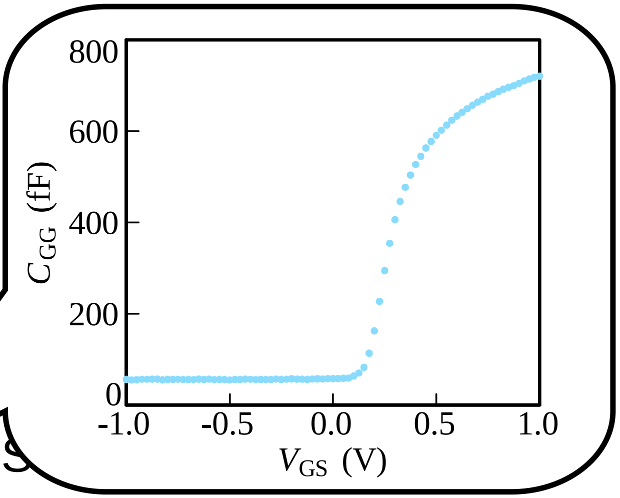
surface potential equation (v)

- approximation required
- 1. neglect holes
  - accumulation region not important for normal MOS operation
  - floating body → holes only visible at very low frequency
- 2. neglect doping
  - doping typically low → $t_{Si} << L_D$
  - doping hardly influences potential
- now integral can be performed

$$\psi(x,y) = v(x) - \ln\left[\frac{\cos^2\left(\sqrt{|\alpha(x)|}\,y/2\right)}{|\alpha(x)|}\right]$$

- use boundary conditions → single algebraic equation
- ψ_s can be solved (implicit equation)

surface potential equation (v)



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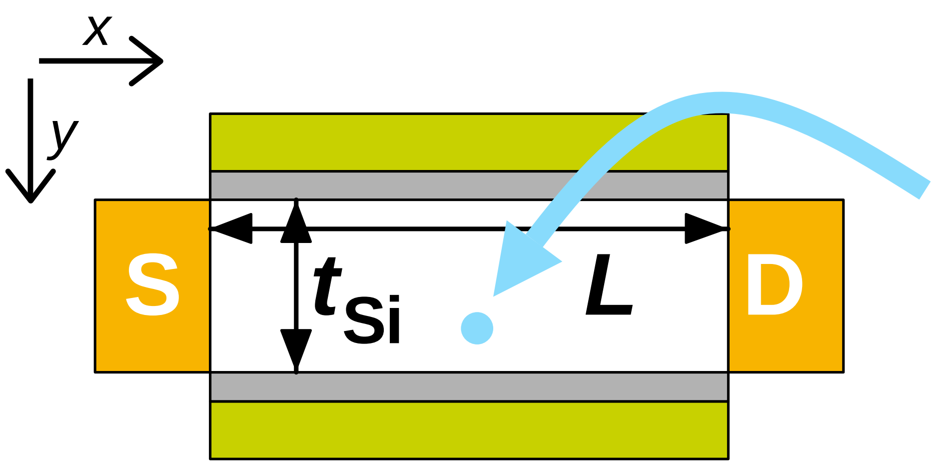
currents and charges (i)

- drift-diffusion gives current density $\boldsymbol{J_D(y)}$ at any *point* in channel

$$-\frac{J_D(y)}{\mu \cdot h} = q(x,y) \cdot \frac{dv}{dx}(x) = \underbrace{q(x,y) \cdot \frac{d\psi}{dx}(x,y)}_{\text{drift}} - \underbrace{\frac{dq}{dx}(x,y)}_{\text{diffusion}}$$



q(x,y) charge density

ψ(x,y) potential

currents and charges (ii)

- drain current (Pao-Sah)

$$I_D = -\mu \cdot \frac{h}{L} \int_0^L \int_{-t_{Si}/2}^{t_{Si}/2} q(x,y) \cdot \frac{dv}{dx}(x)\, dy\, dx$$

- gate charge

$$Q_G = -h \int_0^L \int_{-t_{Si}/2}^{t_{Si}/2} q(x,y)\, dy\, dx$$

- integrals can be performed exactly [1]

[1] H. Lu and Y. Taur, TED 53, p. 1126 (2006)

currents and charges (iii)

- exact result for gate charge:

$$Q_G \propto \frac{1}{I_D}\left(\left[\theta^2 - \ln(\cos^2\theta) - 2\theta\cdot\tan\theta + \frac{4}{3c_{ox}t_{Si}}\theta^3\tan^3\theta + \mathrm{h}(\theta)\right]_{\theta_0}^{\theta_L}\right)$$

$$\mathrm{h}(\theta) = -\frac{2i}{3}\theta^3 - \ln(2)\cdot\theta^2 + (1-\theta^2)\cdot\ln(\cos\theta) - \frac{\theta^2}{2\cos^2\theta} + \theta\tan\theta + i\theta\cdot\mathrm{Li}_2(-e^{2i\theta}) - \frac{1}{2}\mathrm{Li}_3(-e^{2i\theta})$$

$$\theta = \frac{t_{Si}}{4}\sqrt{|\alpha|}$$

$\mathrm{Li}_n(x)$ → polylogarithmic function

current and charges (iv)

- disadvantages of exact solution
  - complicated expressions (involving complex numbers)
  - special functions (polylogarithms)
    - not available in standard (C-)libraries
    - computationally inefficient
  - difficult to include SCEs
- not ideal for compact model

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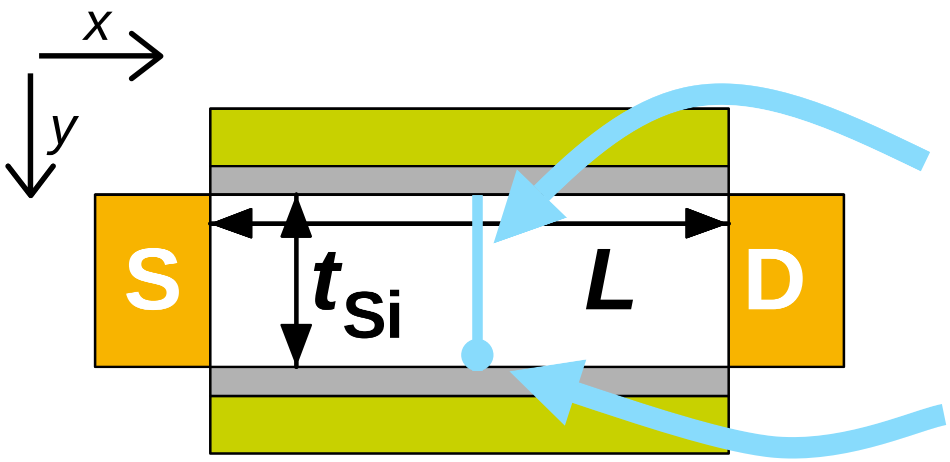
new model – derivation

$$\frac{-J_D(y)}{\mu \cdot h} = q(x,y)\cdot\frac{dv}{dx}(x) = q(x,y)\cdot\frac{d\psi}{dx}(x,y) - \frac{dq}{dx}(x,y)$$

integrate over y

$$\frac{-I_D}{\mu \cdot h} = Q(x)\cdot\frac{dv}{dx}(x) = \tilde{Q}(x)\cdot\frac{d\psi_s}{dx}(x) - \frac{dQ}{dx}(x)$$



$Q(x)$ (integrated) charge density

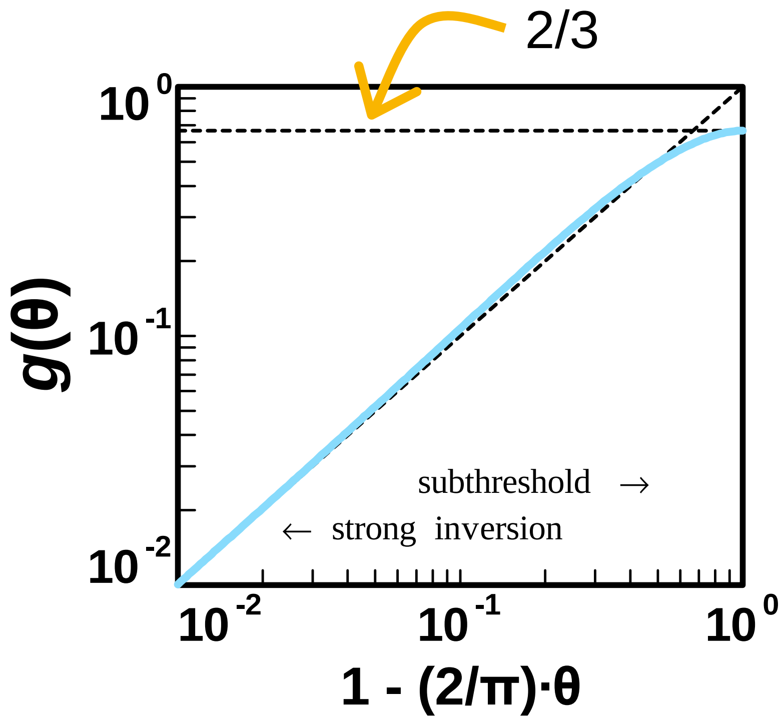
$\psi_s(x)$ surface potential

new model – derivation

- $\tilde{Q} = \int_{-t_{Si/2}}^{t_{Si/2}} q \cdot \frac{d\psi}{dx} dy \bigg/ \frac{d\psi_s}{dx}$ is related to **Q**, but they are *not* equal
- in fact: $\tilde{Q} = Q \cdot \left[1 + \frac{\gamma}{4} \cdot g(\theta)\right]$

where $g(\theta) = \frac{\sin(2\theta) - 2\theta \cdot \cos(2\theta)}{\theta \cdot \tan(\theta) \cdot [2\theta + \sin(2\theta)]}$

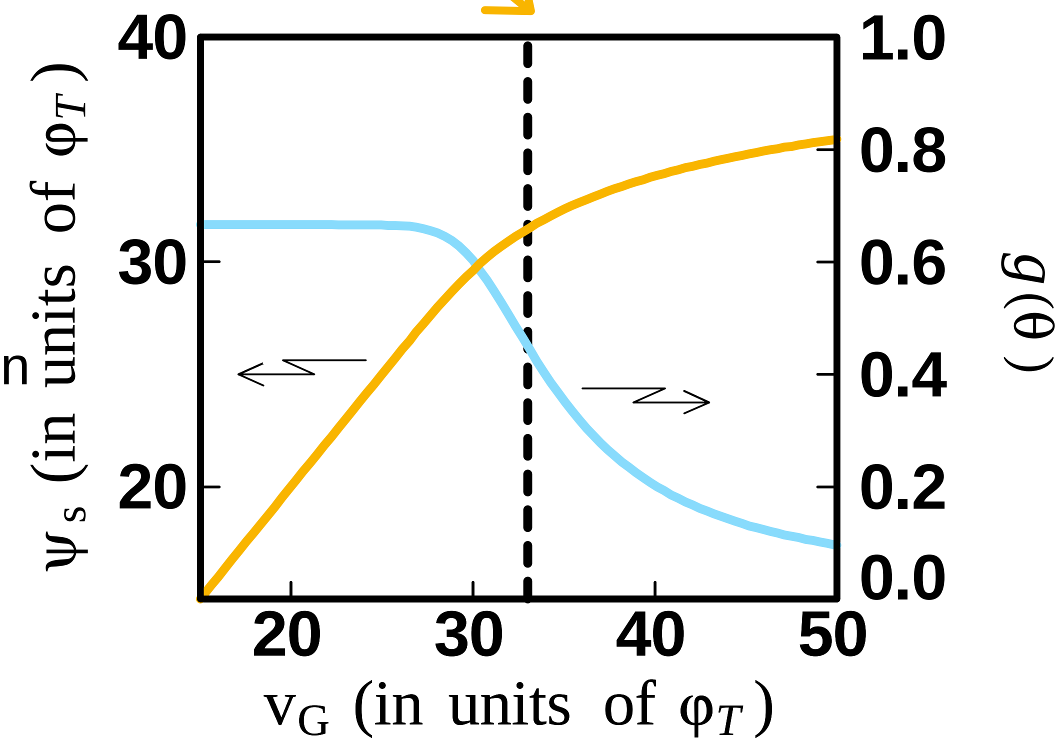
and $\frac{\gamma}{4} \approx \frac{1}{12} \cdot \frac{t_{Si}}{t_{ox}} < 1$ (typical value: 1/2)



new model – derivation

- $\tilde{Q} = Q \cdot \left[1 + \frac{\gamma}{4} \cdot g(\theta)\right]$
- in strong inversion $\tilde{Q} \approx Q$
- $\tilde{Q}$ has *no* influence on diffusion current (subthreshold)
- **conclusion**: approximation $\tilde{Q} \approx Q$ valid in all regions of operation
- **note**: error in *current* is smaller than error in *Q*!

≈ threshold voltage

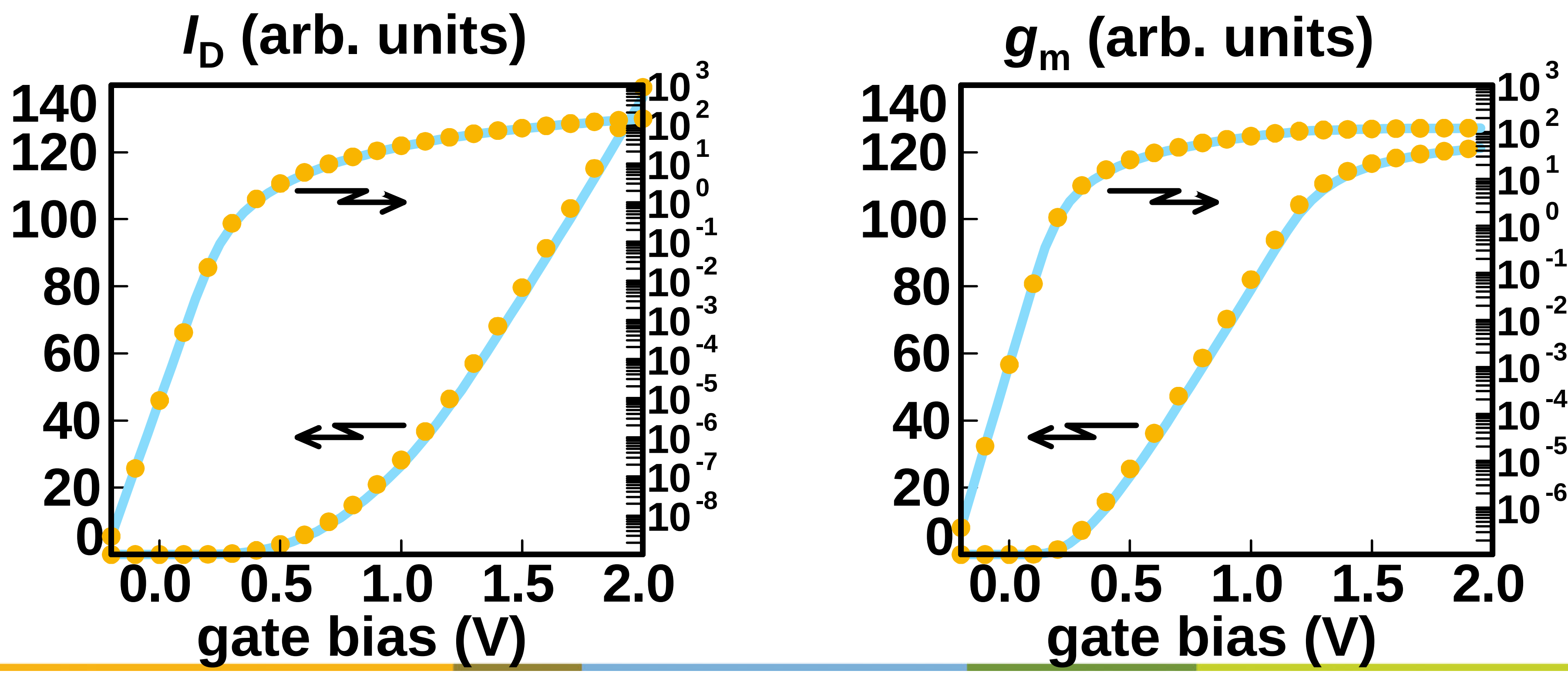


$$-\frac{I_D}{\mu \cdot h} = \tilde{Q}(x) \cdot \frac{d\psi_s}{dx}(x) - \frac{dQ}{dx}(x) \quad \rightarrow \quad Q(x) \cdot \frac{d\psi_s}{dx}(x) - \frac{dQ}{dx}(x)$$

exact — approximation

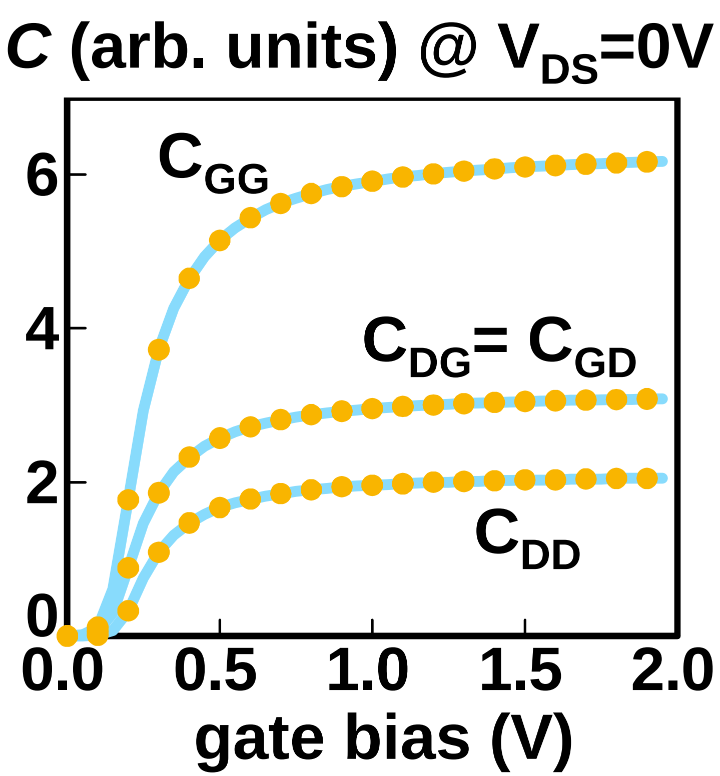
new model – accuracy

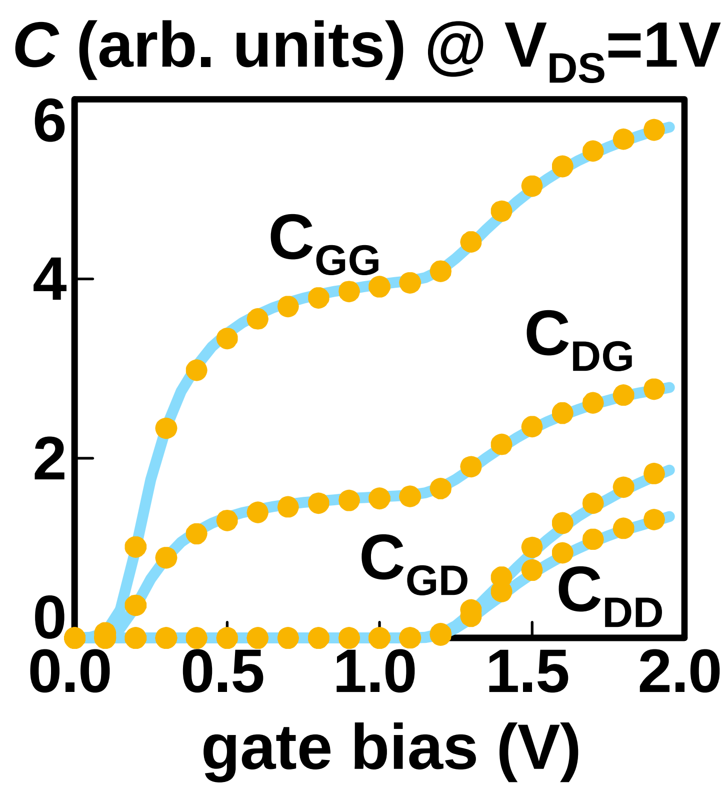
- high accuracy for currents
  - exact calculation (•) vs. our model (—)
  - V_{DS}=1V, no fitting parameters



new model – accuracy

- high accuracy for charges/capacitances
  - exact calculation (•) vs. our model (—)
  - no fitting parameters





new model – equations

- simple expressions
  - for charges

$$Q_G = -h \cdot L \cdot \left[\overline{Q} + \frac{(\Delta Q)^2}{12 \cdot (\overline{Q} - 2 \cdot C_{ox})} \right]$$

$$\overline{Q} = (Q_0 + Q_L)/2 \qquad \Delta Q = Q_L - Q_0$$

$$Q = -\frac{8}{t_{Si}} \theta \tan\theta \qquad \theta = \frac{t_{Si}}{4}\sqrt{|\alpha|}$$

  - and current

$$I_D = -\frac{\mu \cdot h}{2 \cdot L \cdot C_{ox}} \cdot (\overline{Q} - 2 \cdot C_{ox}) \cdot \Delta Q$$

exact:

$$Q_G \propto \frac{1}{I_D}\left(\left[\theta^2 - \ln(\cos^2\theta) - 2\theta \cdot \tan\theta + \frac{4}{3c_{ox}t_{Si}}\theta^3 \tan^3\theta + \mathrm{h}(\theta) \right]_{\theta_0}^{\theta_L} \right)$$

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$$\theta = \frac{t_{Si}}{4}\sqrt{|\alpha|}$$

very suitable for compact model!

new model – benefits

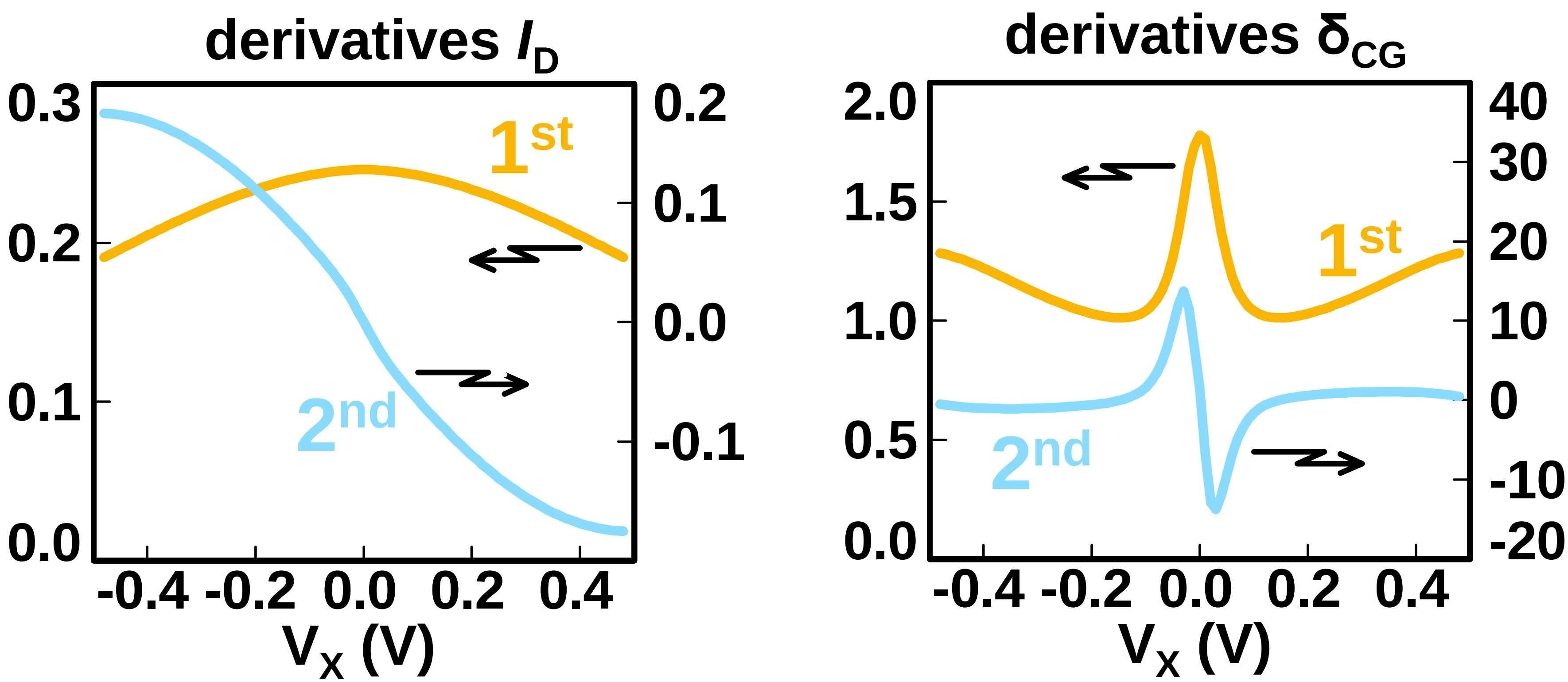
- simple expressions for currents and charges (all in terms of $Q_{x=0}$ and $Q_{x=L}$)
- computationally efficient (no special functions)
- high accuracy (exact at V_{DS}=0)
- approximation preserves essential physics
  - *no* charge-sheet approximation (despite similar equations)
  - volume inversion effect correctly modelled
- current/charge expressions similar to bulk MOSFET
  - SCEs can be included along the same lines
- no loss of symmetry properties

short channel and additional effects

- core model describes ideal classical long channel device
- practical model needs to describe *real* devices, including
  - velocity saturation
  - channel length modulation
  - quantum confinement
  - mobility reduction
  - …
- implemented descriptions adopted from PSP bulk-MOSFET model

Gummel symmetry

- important for analog simulation
  - related to S/D symmetry
  - see: McAndrew, TED53 p. 2202 (2006)



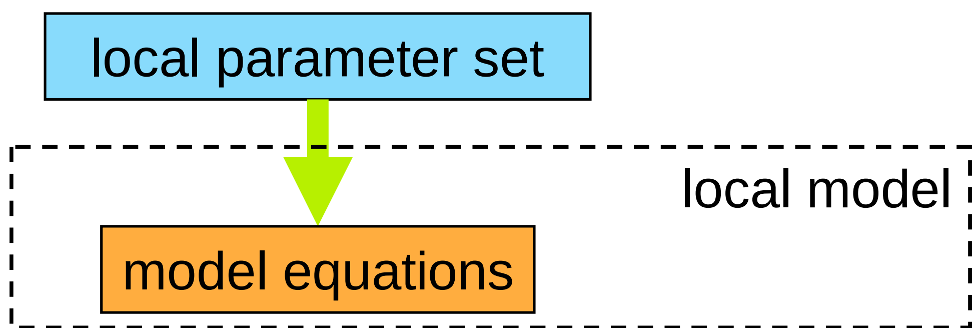
geometry scaling

geometry scaling

- extraction procedure (similar to PSP)
  - local parameter set for each *L*
  - fit scaling rules to local parameters
  - create global parameter set
- 2D-device simulations
  - symmetric FinFET
  - p-channel
  - L=30…400nm
  - t_{Si}=10nm, t_{ox}=1.2nm

geometry scaling – local/global model

- local parameter set: describes one single device (geometry)
  ~14 parameters (IV + CV)
- global parameter set: describes full range of *L*-values (~30 parameters)



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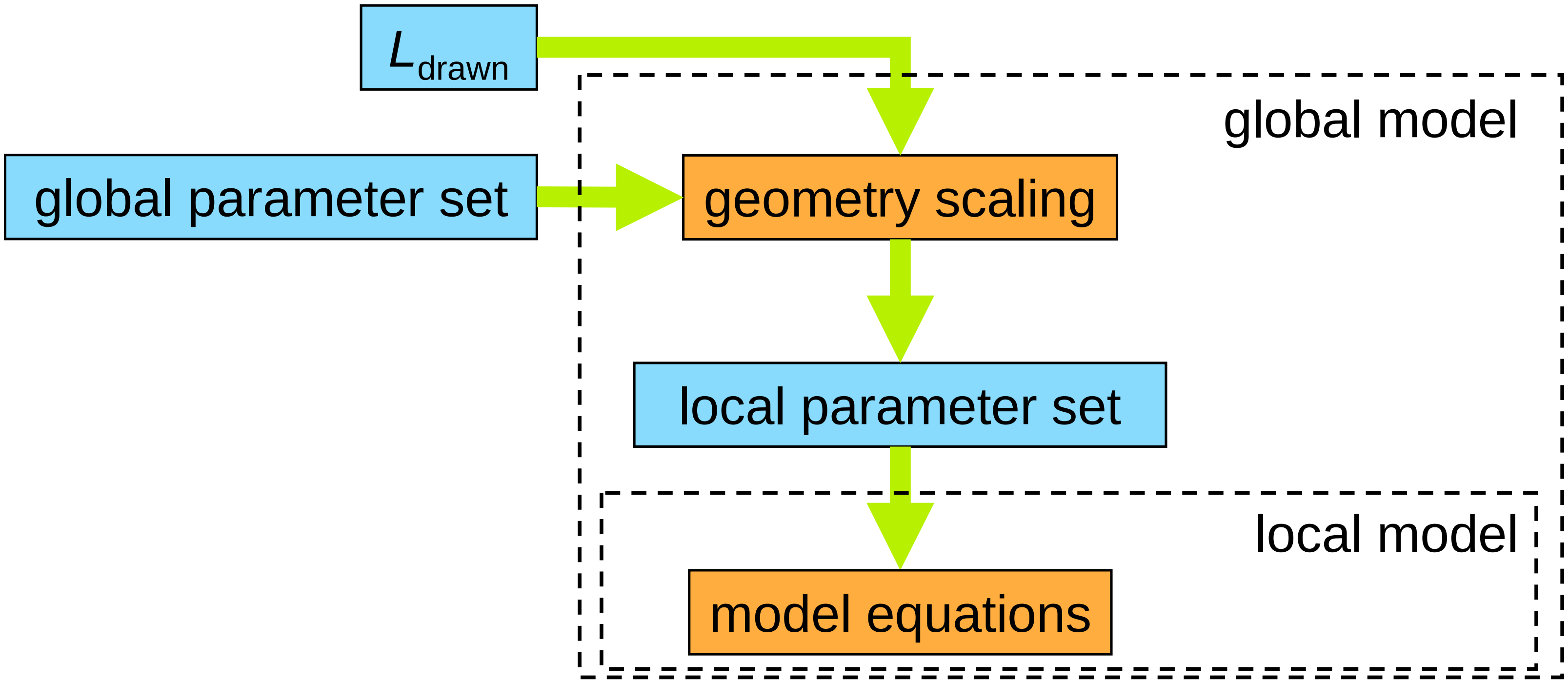


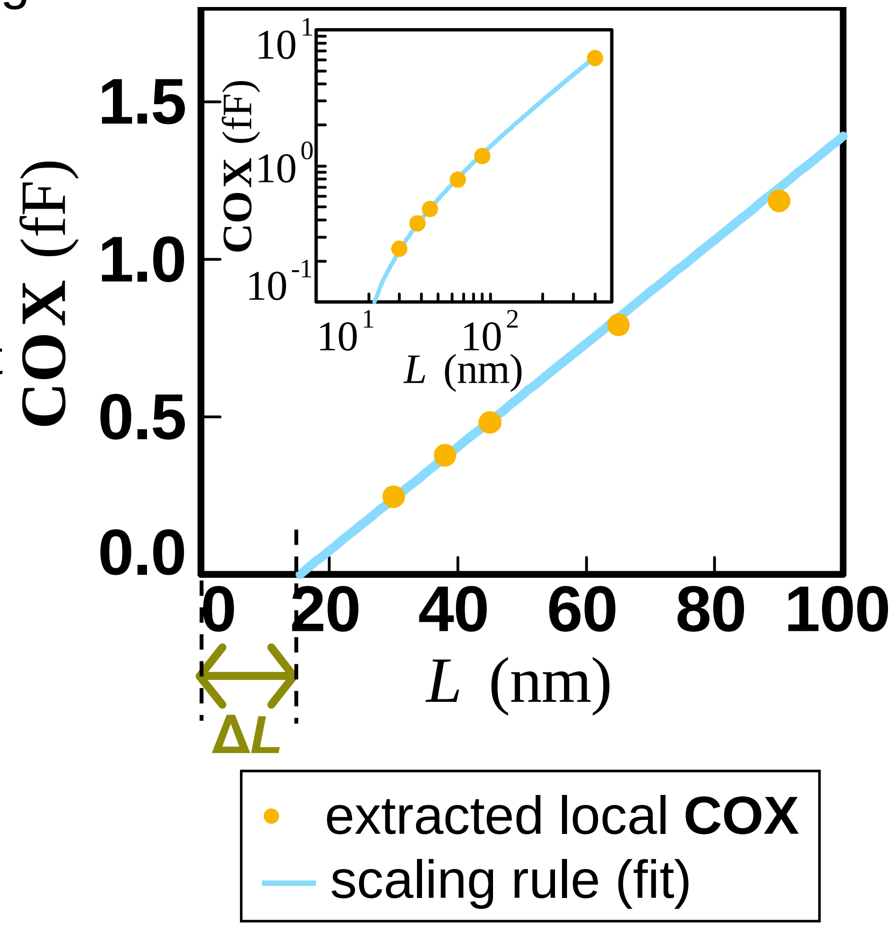
geometry scaling – effective channel length

- determination of effective channel length

$$COX = \frac{\varepsilon_{ox}}{t_{ox}} \cdot W_{eff} \cdot (L - \Delta L)$$

- requires accurate value for **COX**
  - usually taken from accumulation capacitance
  - but accumulation capacitance cannot be measured in floating-body device
  - C_{GG} is V-dependent in inversion
  - QM-effects must be included
- accurate CV-model required!
- edge-effects (top gate, burried oxide) included trough *effective* fin-height

$$W_{eff} \approx 2 \cdot h_{fin,eff}$$



geometry scaling – effective channel length

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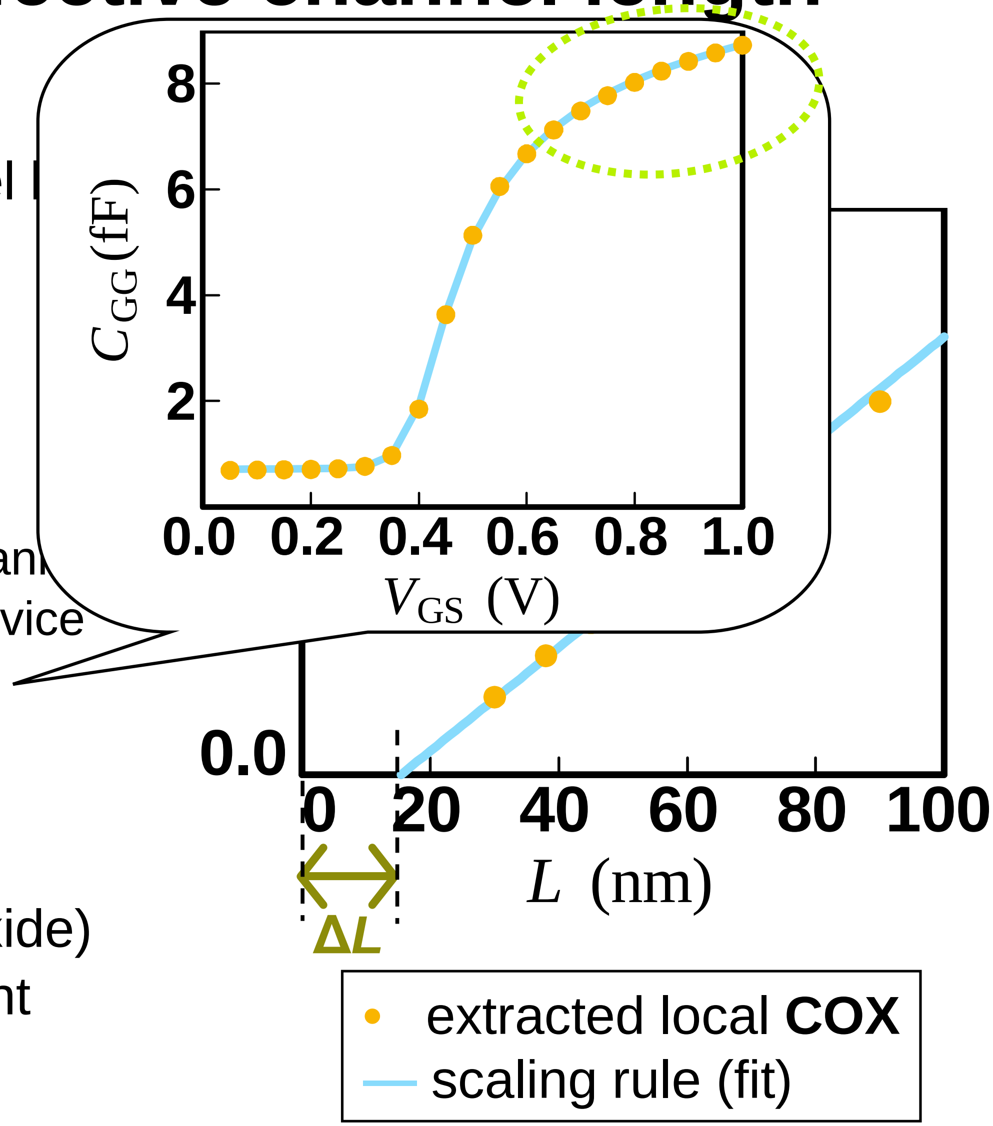


geometry scaling – scaling rules

- fit scaling rules to local model parameters
- example: non-ideal subthreshold slope ***S*** in short devices

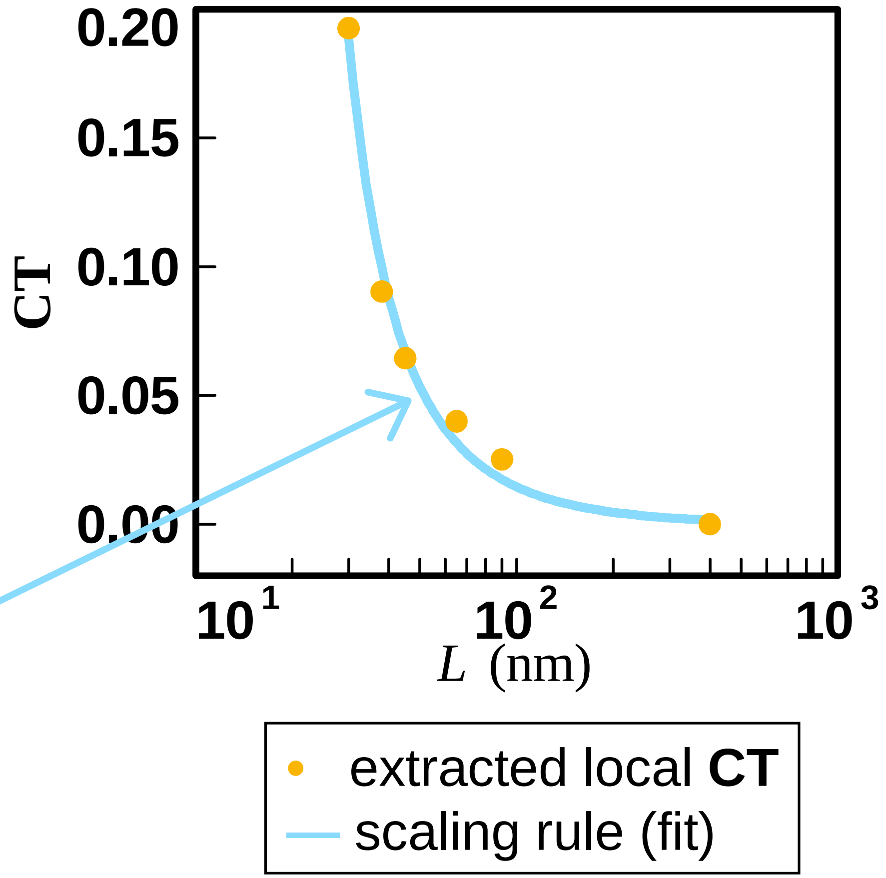
$$S = S_{\text{long channel}} \cdot (1 + \text{CT})$$

- scaling rule

$$\text{CT} = \text{CTO} + \text{CTL} \cdot \left(\frac{L_{EN}}{L_E} \right)^{\text{CTLEXP}}$$

- fit to extracted local parameters

CTO = 0
CTL = 0.0004
CTLEXP = 1.5



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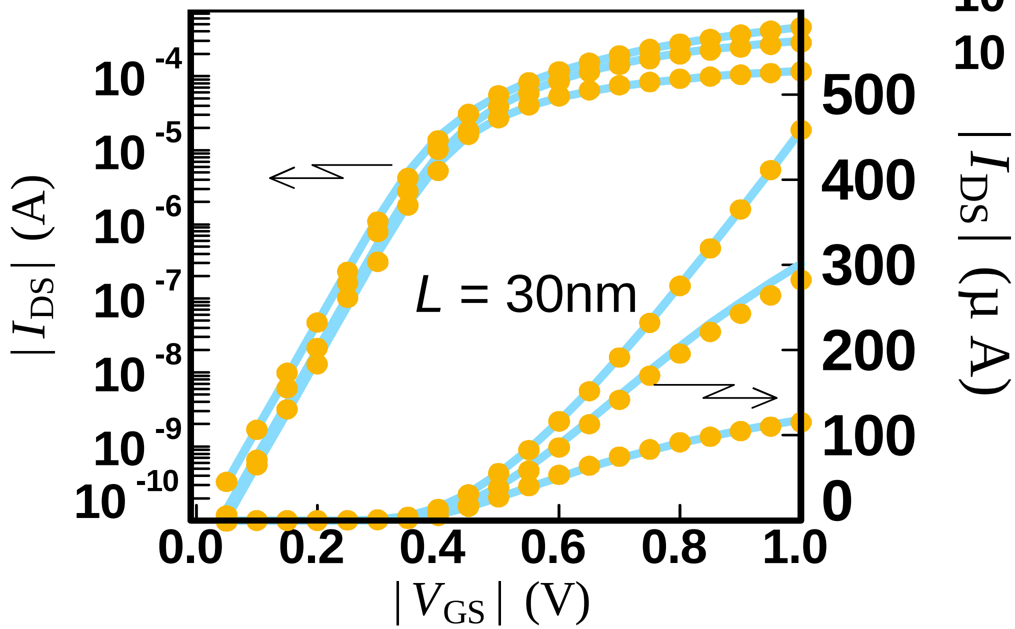
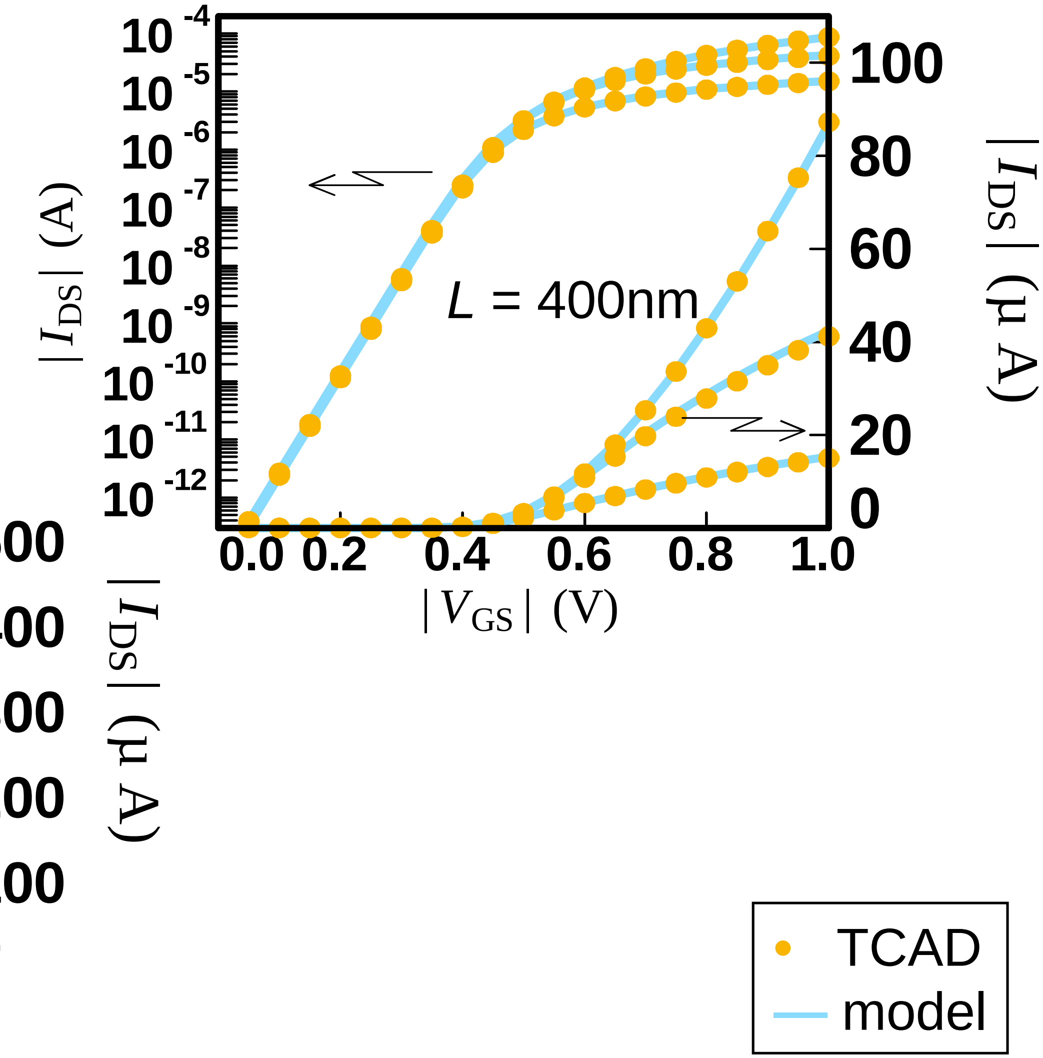
geometry scaling – results *IV*

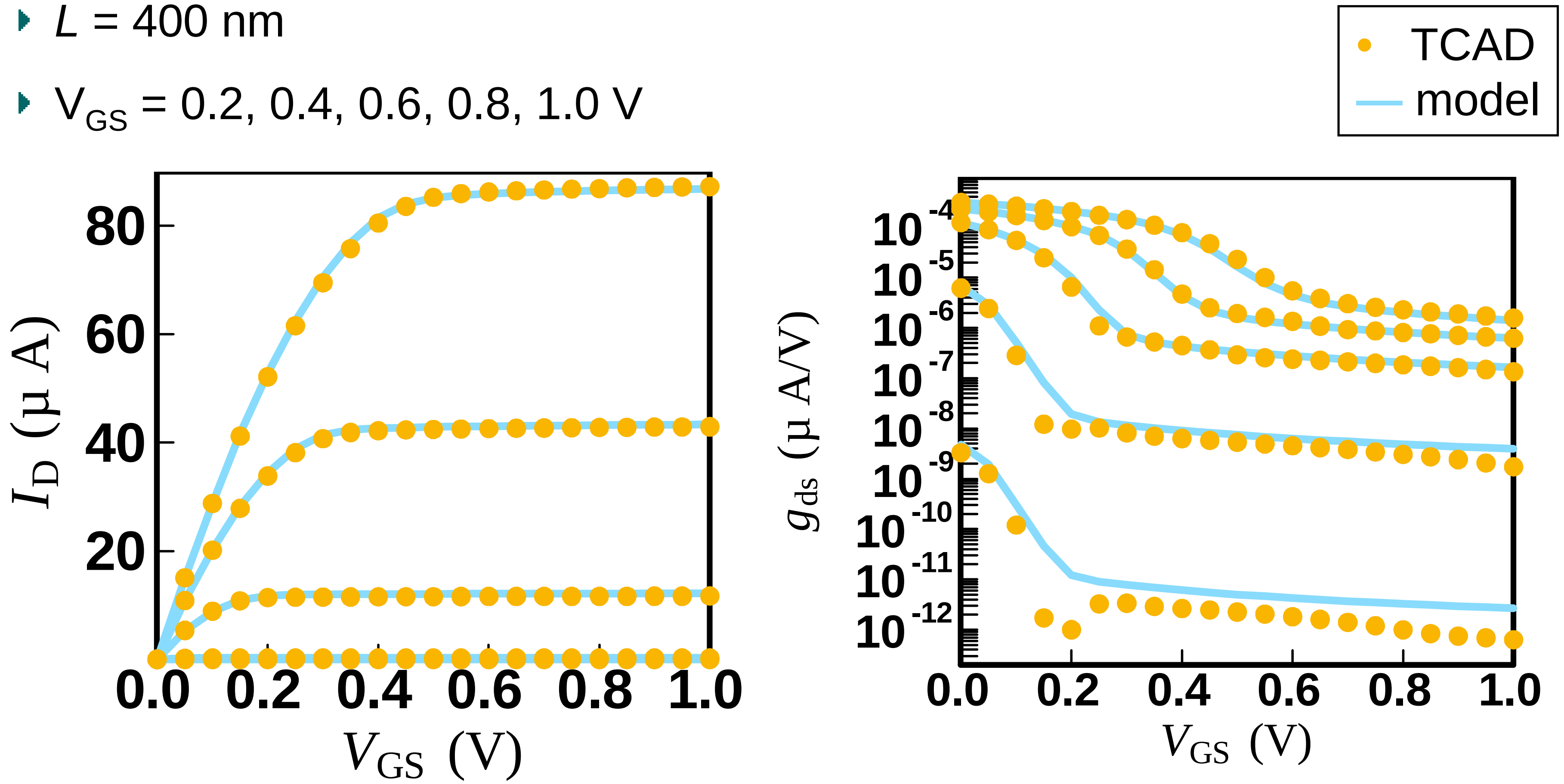
- Resulting global model fits
- V_{DS} = 0.05, 0.15, 1.0 V





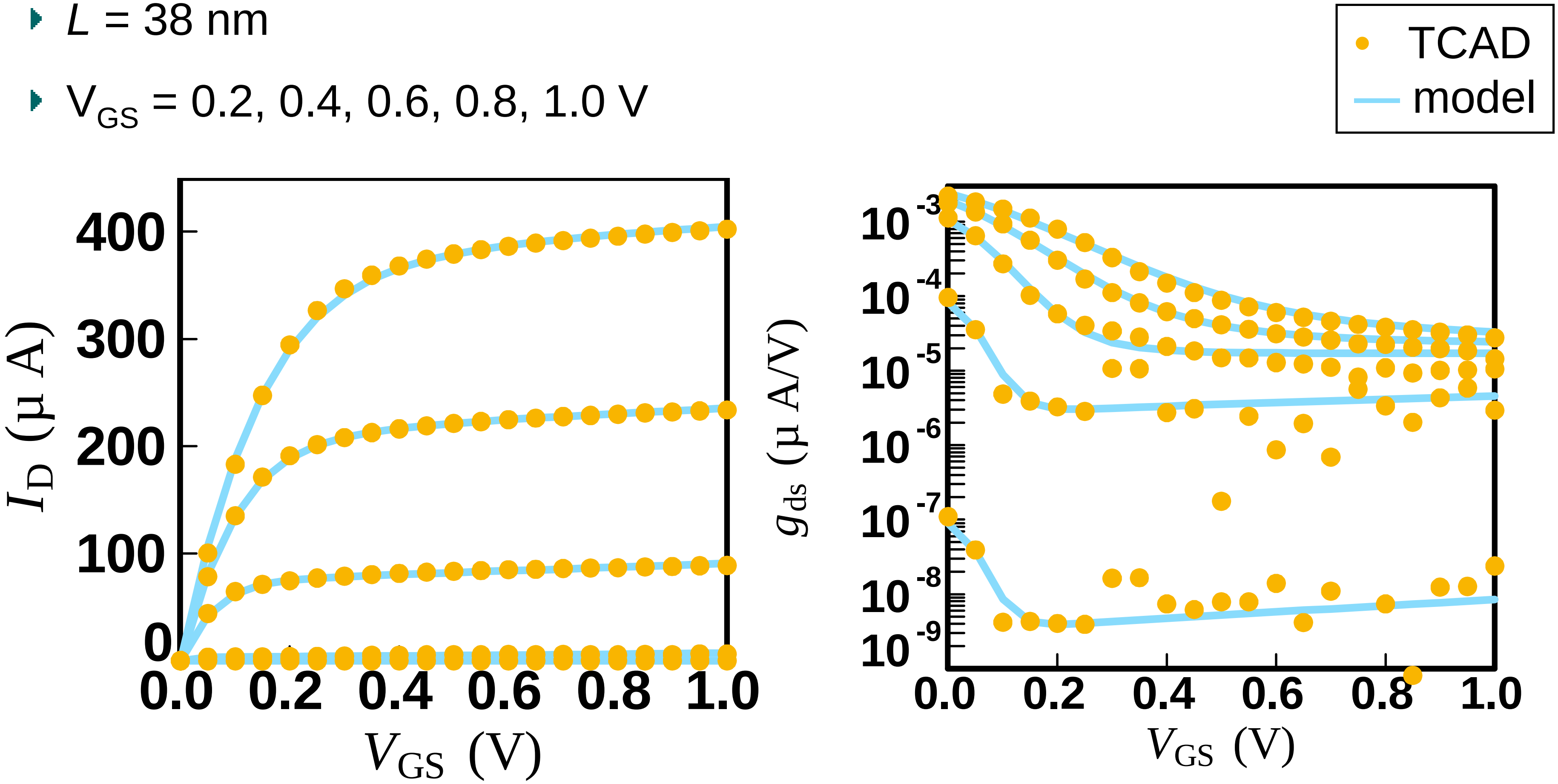
geometry scaling – results *IV*

- L = 400 nm
- V_{GS} = 0.2, 0.4, 0.6, 0.8, 1.0 V

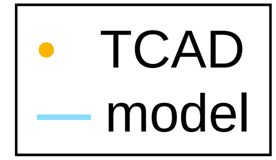


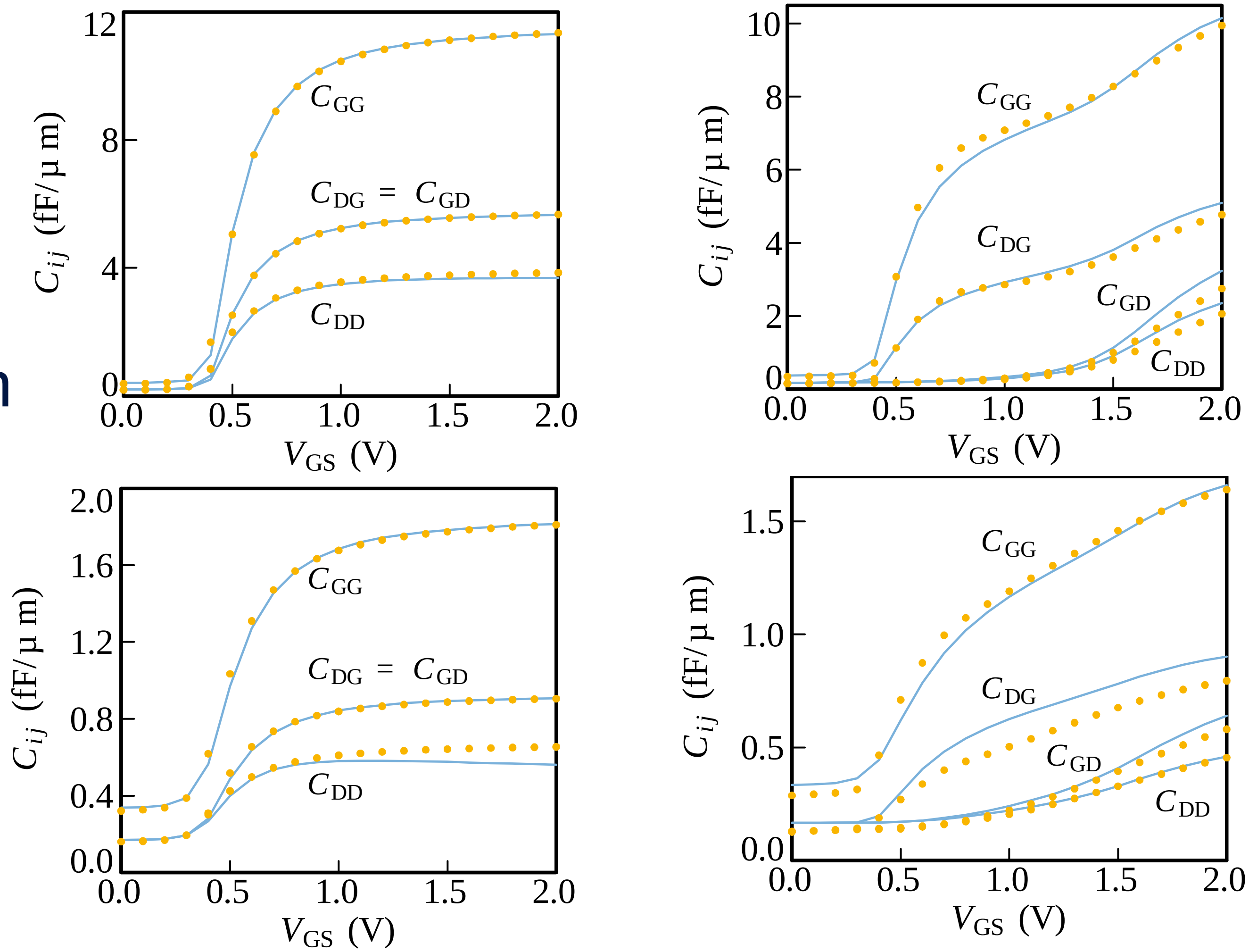
geometry scaling – results *IV*

- L = 38 nm
- V_{GS} = 0.2, 0.4, 0.6, 0.8, 1.0 V



geometry scaling – results *CV*





L=200nm

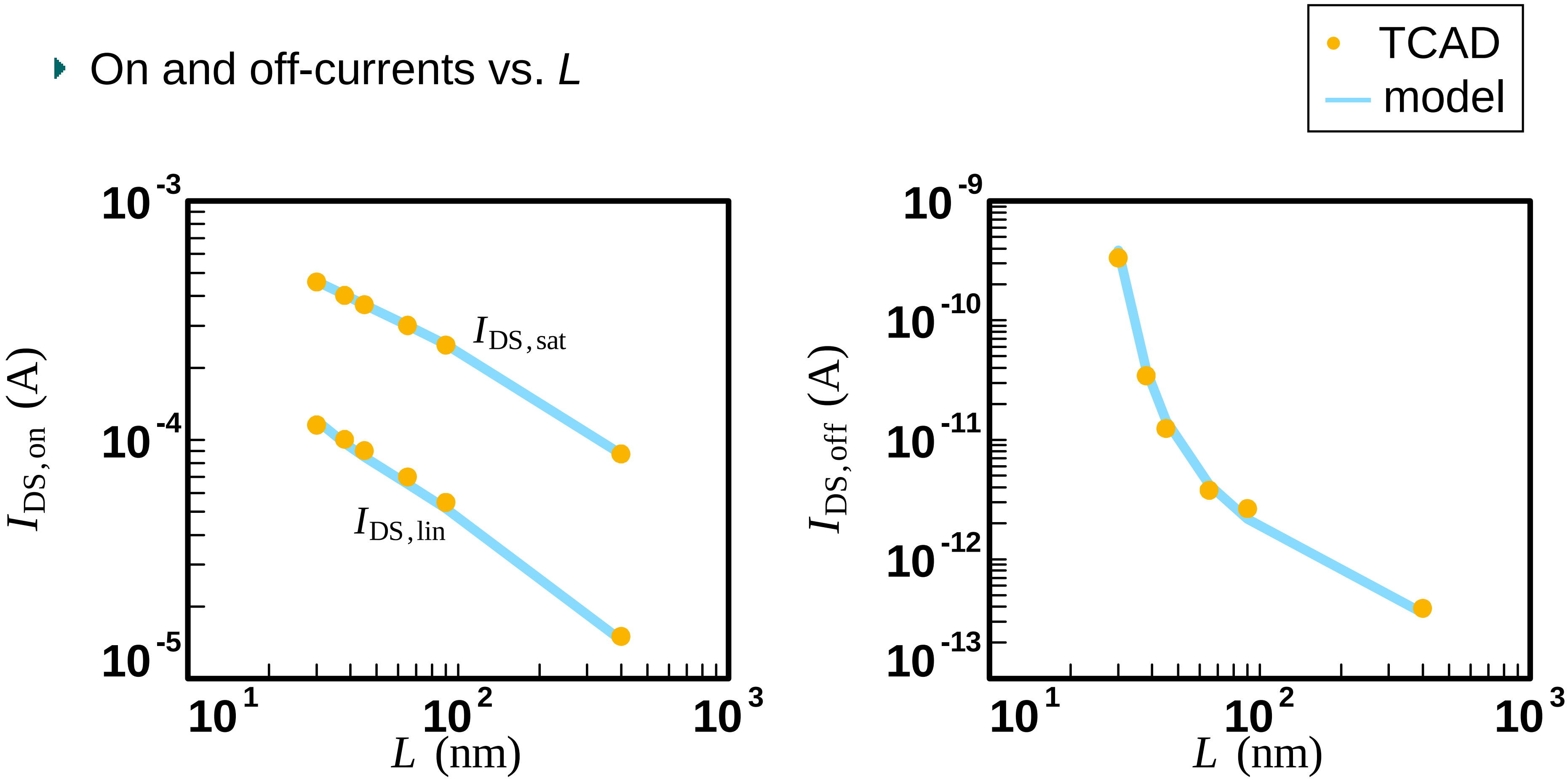
L=30nm

V_{DS}=0V

V_{DS}=1.0V

geometry scaling – on/off currents

- On and off-currents vs. *L*



V_{GS}=1, V_{DS}=50 mV / 1V

V_{GS}=0, V_{DS}=1V

model overview / summary

- implemented in Verilog-A
- true *compact* model
  - no extensive numerical algorithms
- includes all operating regions
  - sub-threshold
  - linear/triode
  - saturation
- suitable for all analysis types
  - dc
  - ac
  - transient
  - HB, PSS, …
- hierarchy (for easy parameter extraction)
  - local and global model

conclusion

- PSP-based compact FinFET model
- PSP bulk-MOSFET model elements have been reused
- compact and computationally efficient
- model gives excellent description of
  - currents (subthreshold, linear, saturation)
  - conductances
  - capacitances
- model covers full range of channel lengths