PSP-based compact FinFET model

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Introduction

- FinFETs are candidates as replacements for bulk MOSFETs
  - Better control of short channel effects
  - Double drive current
- Compact model development
  - Compact model required for circuit design
  - No (public domain) FinFET models available
- Extending the PSP-family
  - Bulk CMOS
  - PD-SOI
  - FD-SOI
  - FinFET
  - …
- FD-device: fundamentally different electrostatics
  - touches the heart of a compact model

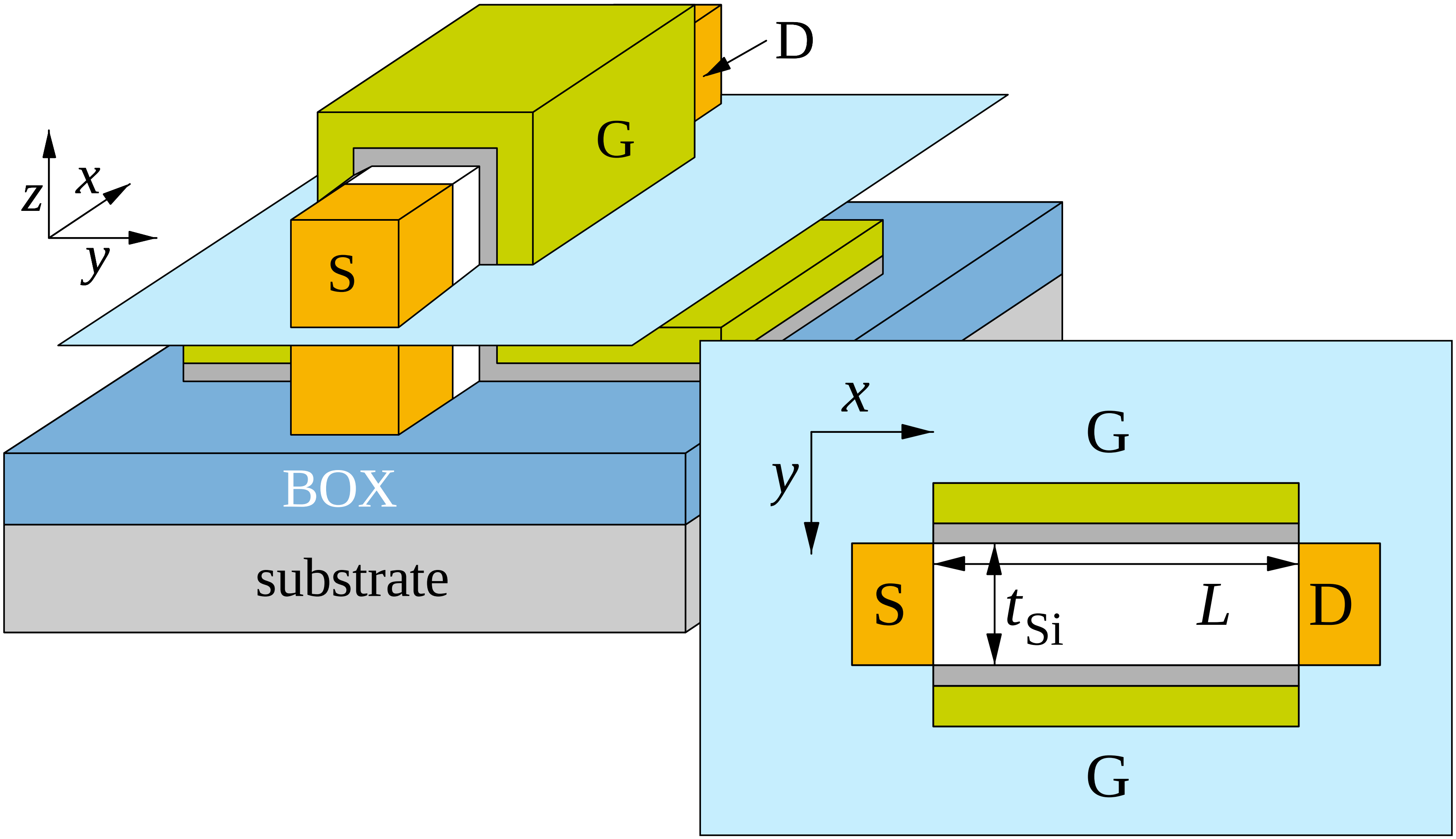
Requirements

- physics based
  - scaling
  - variability
- pay attention to
  - derivatives (up to 3rd order)
  - symmetry (S/D exchange)
- stay within PSP-framework
  - surface potential
  - reuse of existing knowledge

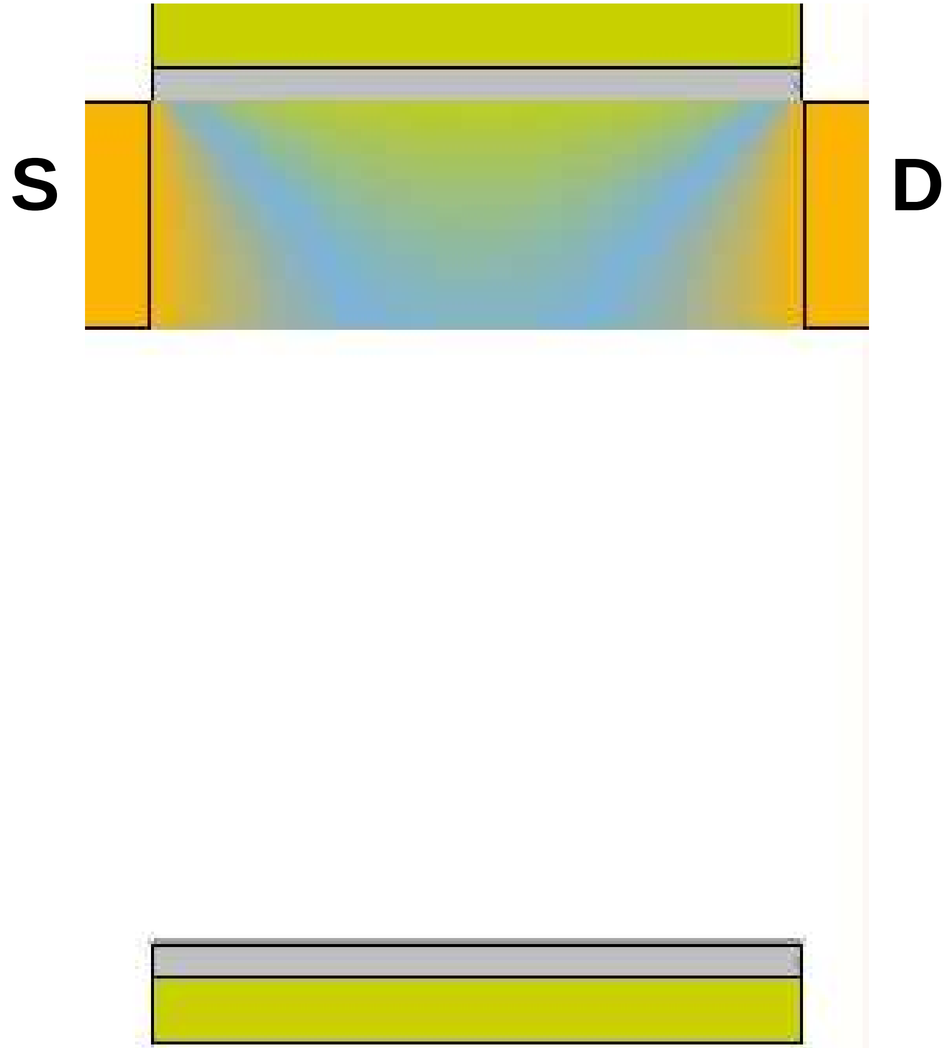
Outline

- Introduction
- Surface potential equation
  – Planar vs. FinFET/DG-FET/FD-SOI
- Currents and charges
- Short channel effects
- Verification
- Model overview
- Conclusion

Device

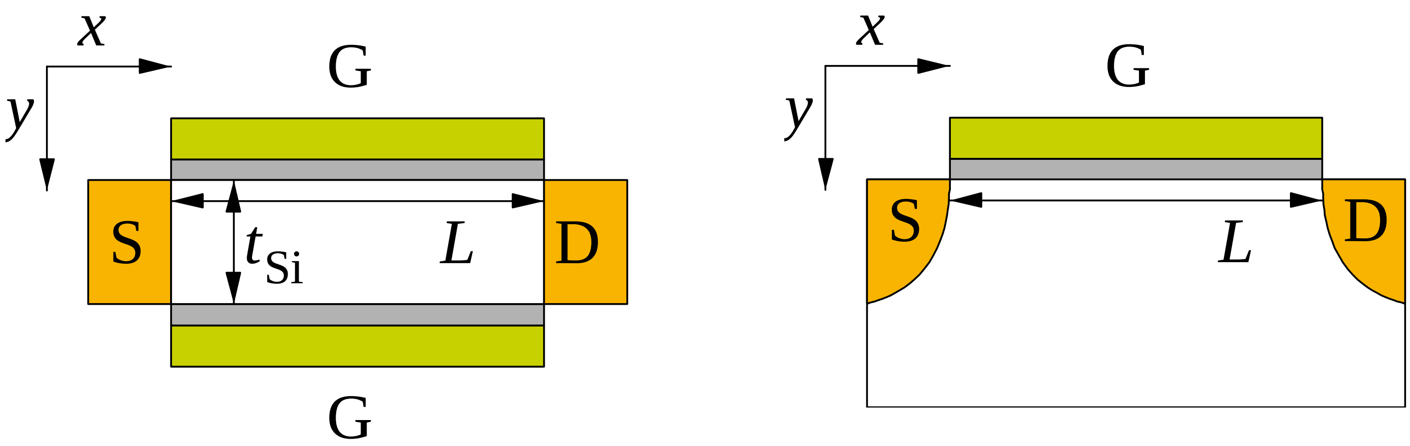


Channel control in FinFET



(animation)

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 $\rho = -q \cdot N_A \cdot \left(1 + e^{-q\cdot(V+\varphi_B)/k\cdot T} \cdot e^{q\cdot\psi/k\cdot T} - e^{-q\cdot\psi/k\cdot T}\right)$

dope electrons holes

Surface potential equation (ii)

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

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

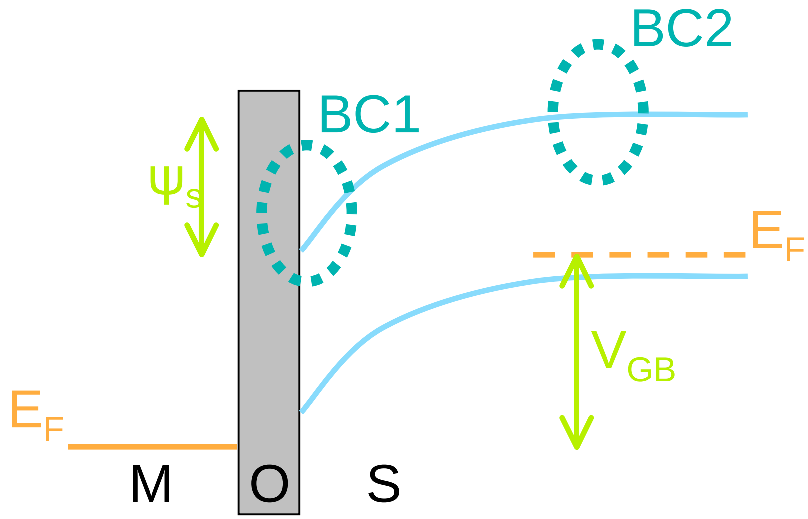
Surface potential equation (iii)

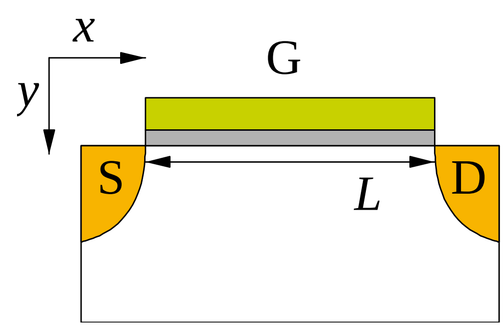
- Bulk MOSFET

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

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

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



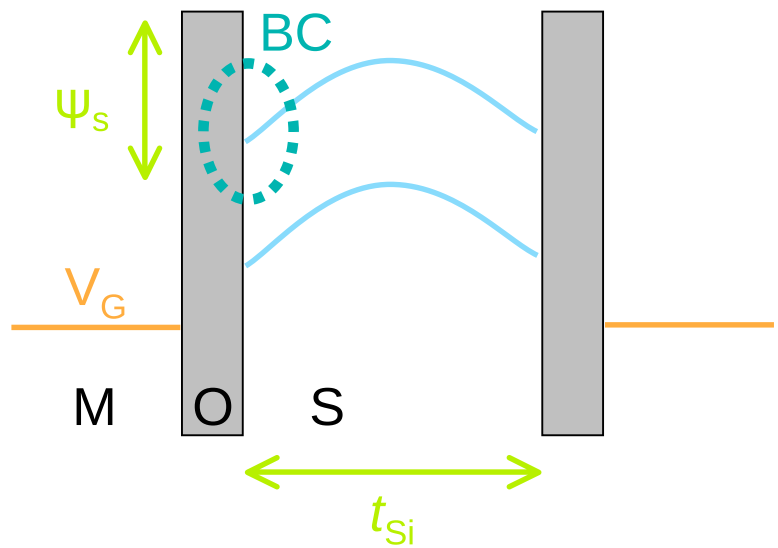


Surface potential equation (iv)

- FinFET

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

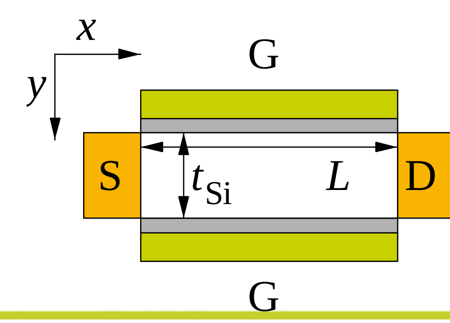
- BC: $\psi' = C_{ox}(\psi_s - V_G^*)$



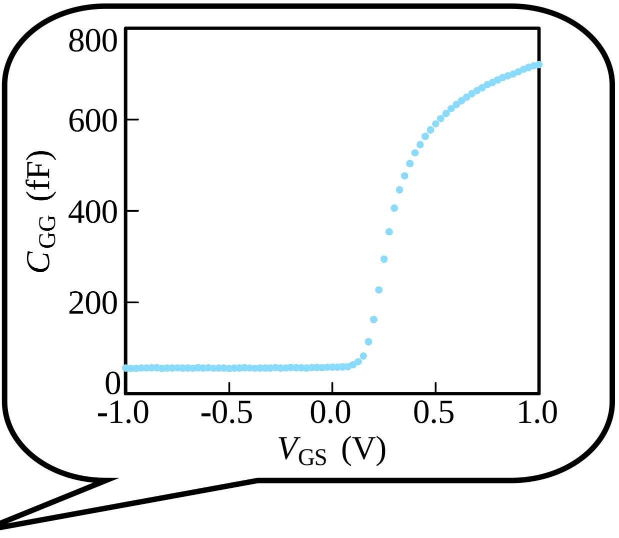
- ψ_s cannot yet be solved
- need second integration step

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

- Two equation, including integral



Surface potential equation (v)



- Approximation required
- Neglect holes
  - Not required for normal MOS operation
  - Floating body → only visible at extremely low *f*
- Neglect doping
  - Doping typically low → does hardly influence potential
  - Can be included as perturbation later
- Now integral can be performed

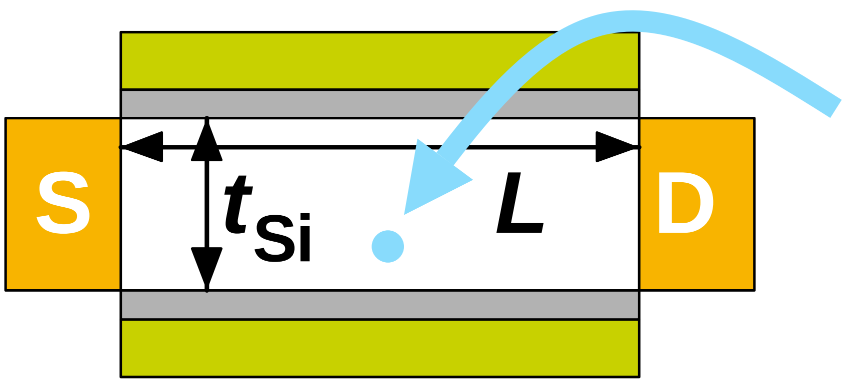
$$\psi(x,y) = v(x) - \ln\left[\frac{\cos^2\left(\sqrt{|\alpha(x)|}\,y/2\right)}{|\alpha(x)|}\right]$$

- Combine with boundary conditions: single algebraic equation
- ψ_s can be solved

currents and charges (i)

- drift-diffusion gives at any point in channel

$$I_D(y) \propto q(x,y)\cdot\frac{dv}{dx}(x) = \underbrace{q(x,y)\cdot\frac{d\psi}{dx}(x,y)}_{\textbf{drift}} - \underbrace{\frac{dq}{dx}(x,y)}_{\textbf{diffusion}}$$



q(x,y) **charge density**
ψ(x,y) **potential**

currents and charges (ii)

- drain current (Pao-Sah)

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

- gate charge

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

- double 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

not suitable for compact model!

current and charges (iv)

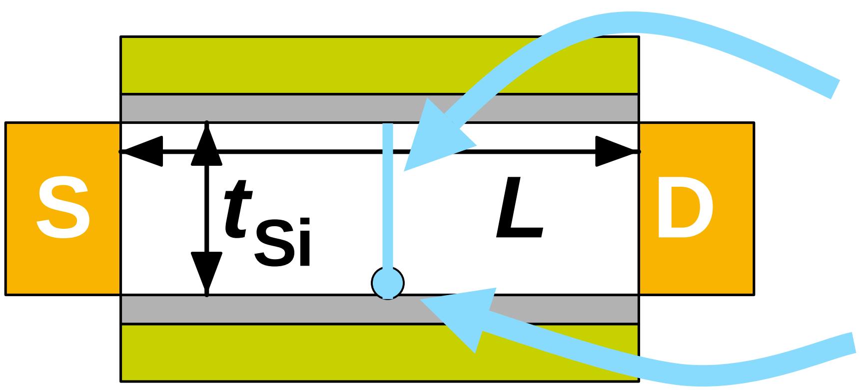
- disadvantages of exact solution
  - complicated expressions (complex numbers)
  - special functions (polylogarithms)

    → computationally inefficient
  - difficult to include SCEs

new model (i)

- Pao-Sah: $$I_D = -\mu \cdot \frac{W}{L} \int_0^L \int_{-t_{Si}/2}^{t_{Si}/2} q(x,y) \cdot \frac{dv}{dx}(x)\, dy\, dx$$
- first integrate over *y* only

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



Q(x) (integrated) charge density

$\psi_s(x)$ surface potential

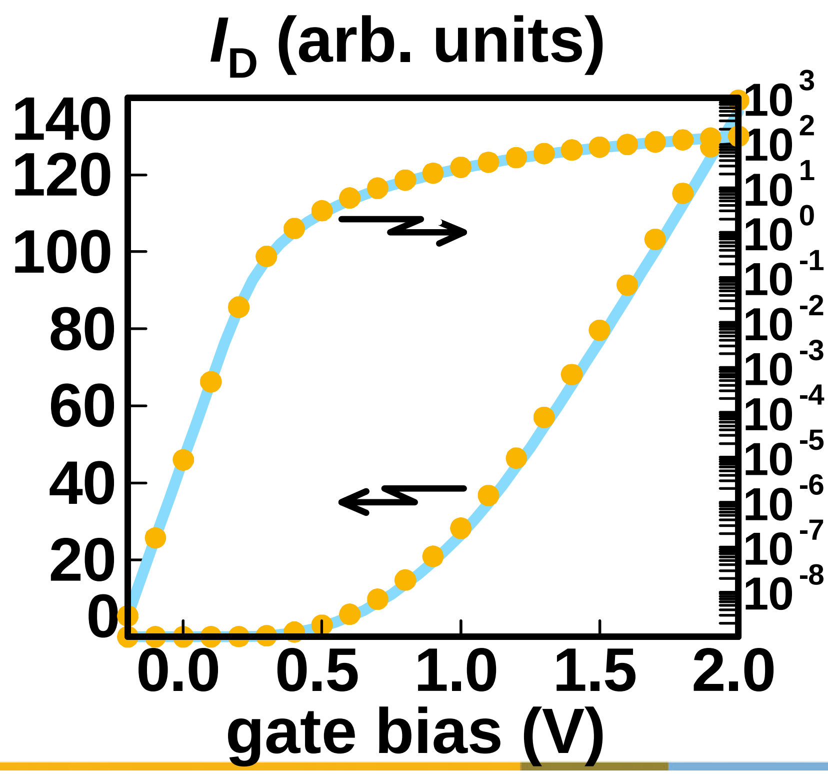
new model (ii)

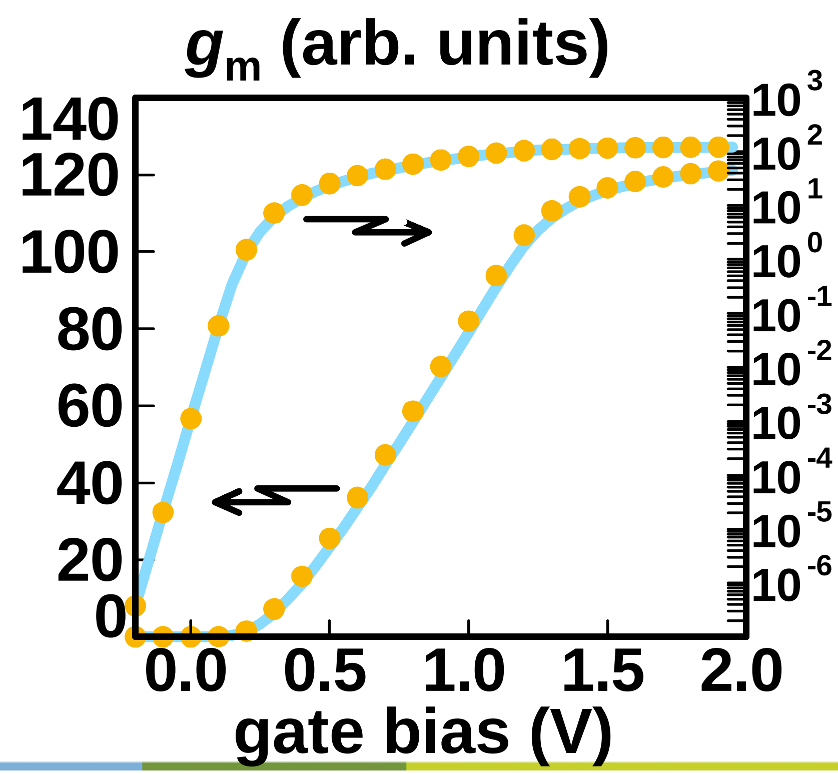
- $\tilde{Q}$ can be computed explicitly
- $\tilde{Q} \approx Q$ in strong inversion
- $\tilde{Q}$ occurs only in *drift* component of current
  → approximation can be used
  in all regions of operation

$$I_D \propto \tilde{Q}(x) \cdot \frac{d\psi_s}{dx}(x) - \frac{dQ}{dx}(x) \quad \Rightarrow \quad I_D \propto Q(x) \cdot \frac{d\psi_s}{dx}(x) - \frac{dQ}{dx}(x)$$

new model (iii)

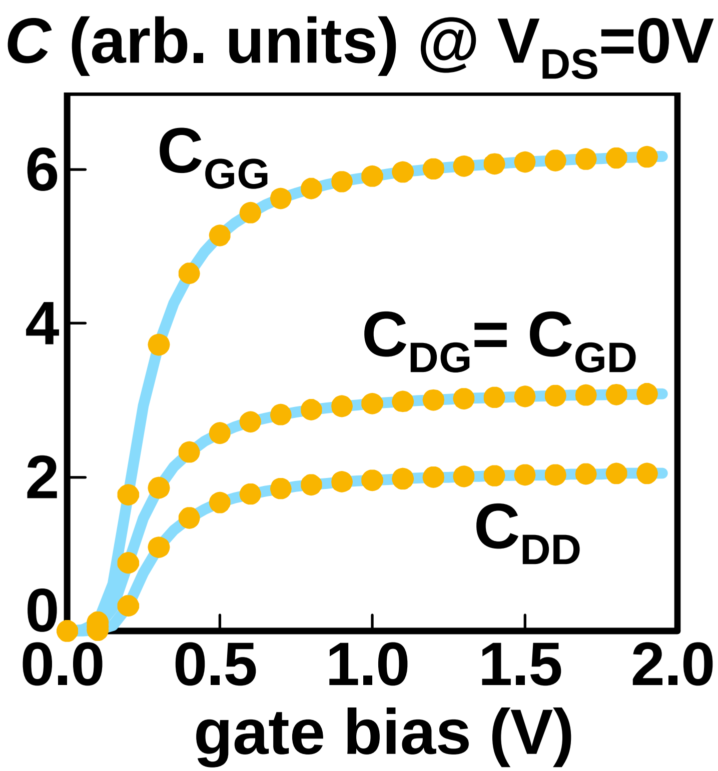
- high accuracy for currents
  - exact calculation (•) vs. our model (—)
  - V_{DS}=1V, no fitting parameters

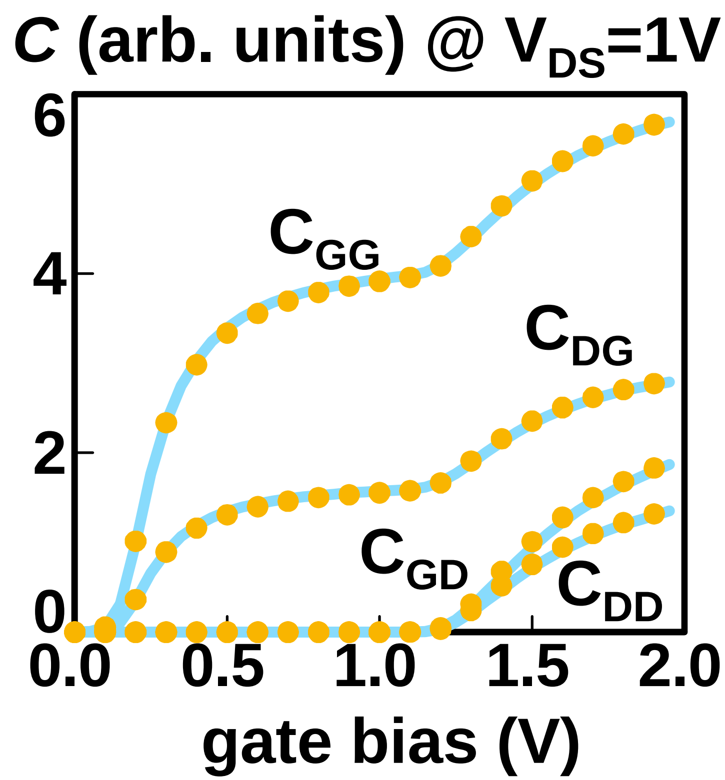




new model (iv)

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





new model (v)

- simple expressions for charges

$$Q_G \propto \overline{Q} + \frac{(\Delta Q)^2}{12(\overline{Q} - 2C_{ox})}$$

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

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

- and current

$$I_D \propto -C_{ox} \cdot (\overline{Q} - 2C_{ox}) \cdot \Delta Q$$

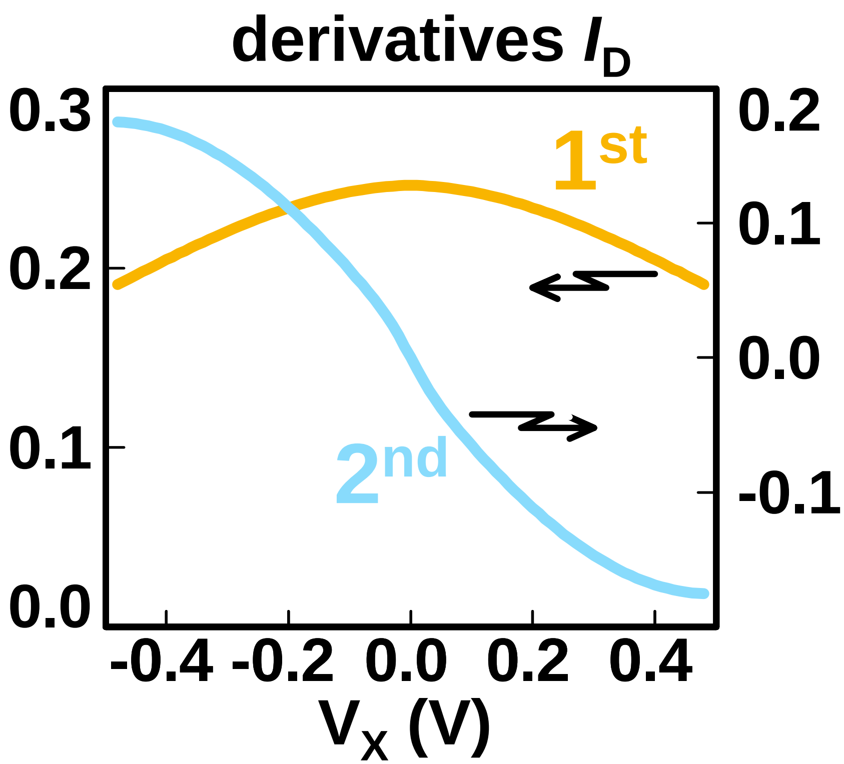
very suitable for compact model!

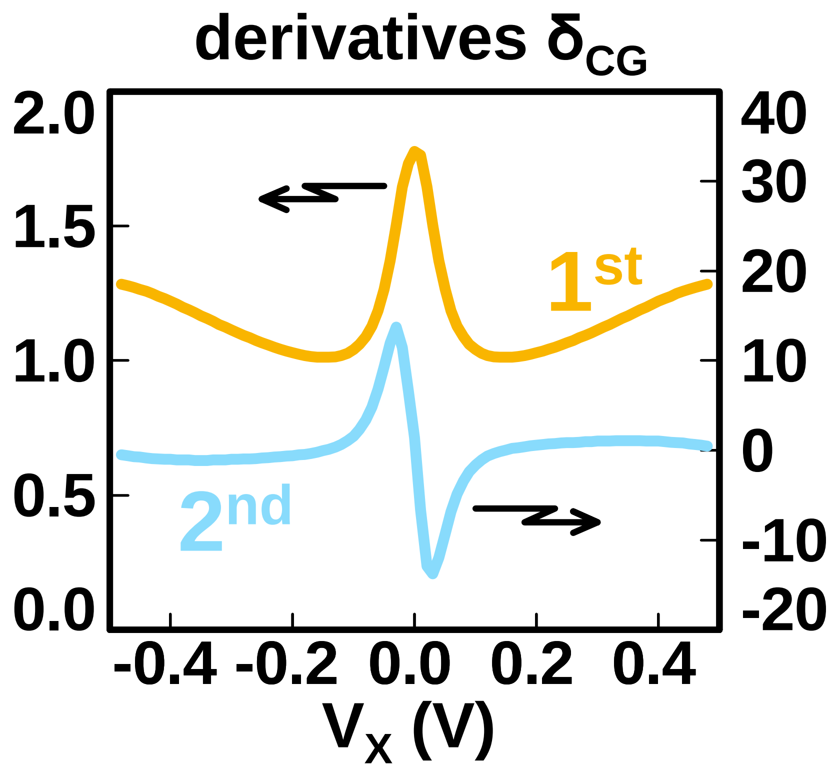
new model (vi)

- simple expressions for currents and charges (all in terms of Q_0 and Q_L)
- no special functions → computationally efficient
- high accuracy (exact at V_{DS}=0)
- reminiscent of CSA-result for bulk MOSFET
  - easy(er) to include SCEs
  - essential physics preserved
  - different physical origin
  - NO charge-sheet approximation made!
- no loss of symmetry properties

Gummel symmetry

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



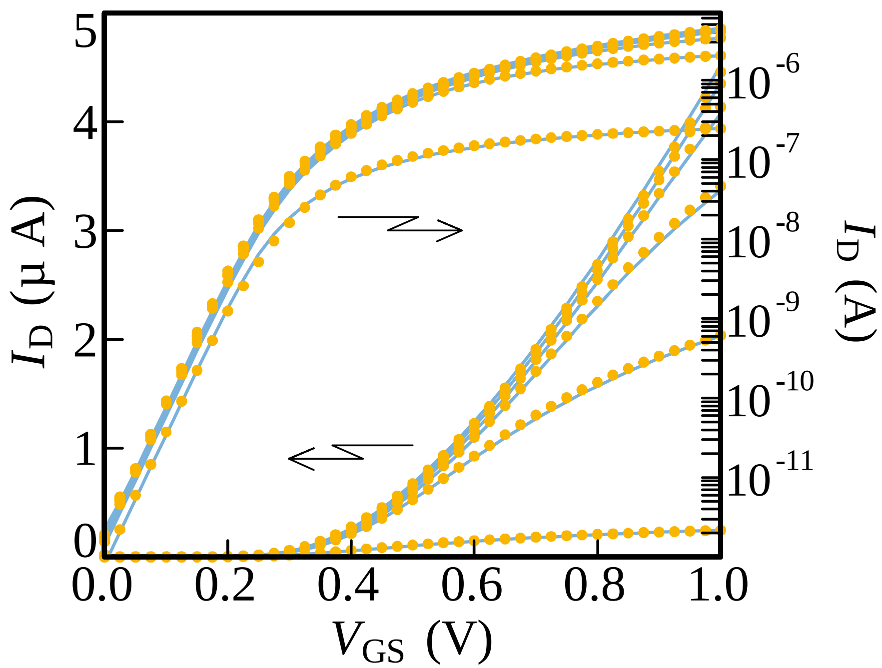


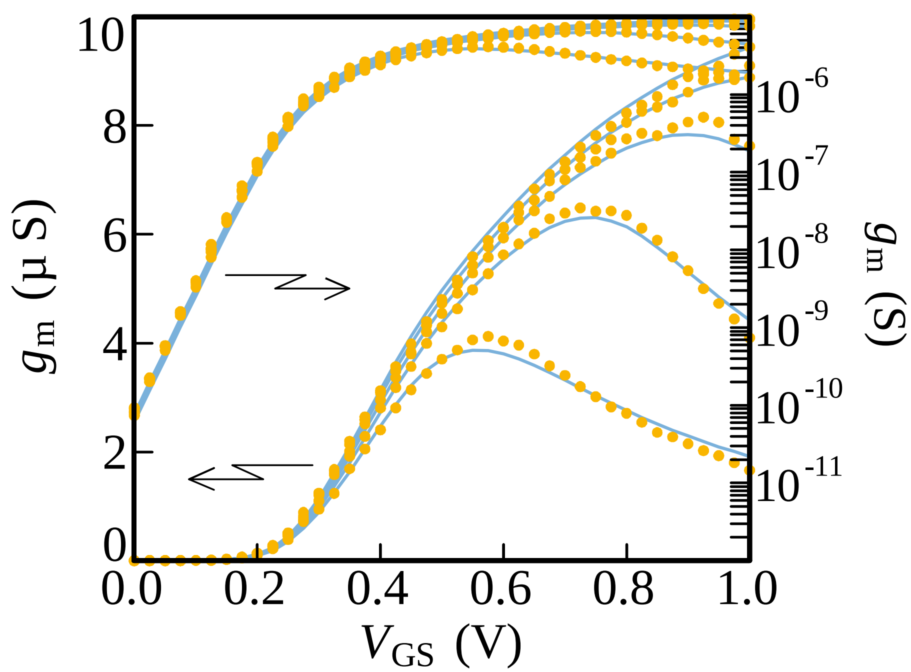
Additional effects

- additional non-ideal effects included
  - velocity saturation
  - channel length modulation
  - quantum confinement
  - mobility reduction
- taken (*mutatis mutandis*) from the PSP model

I-V (long channel)

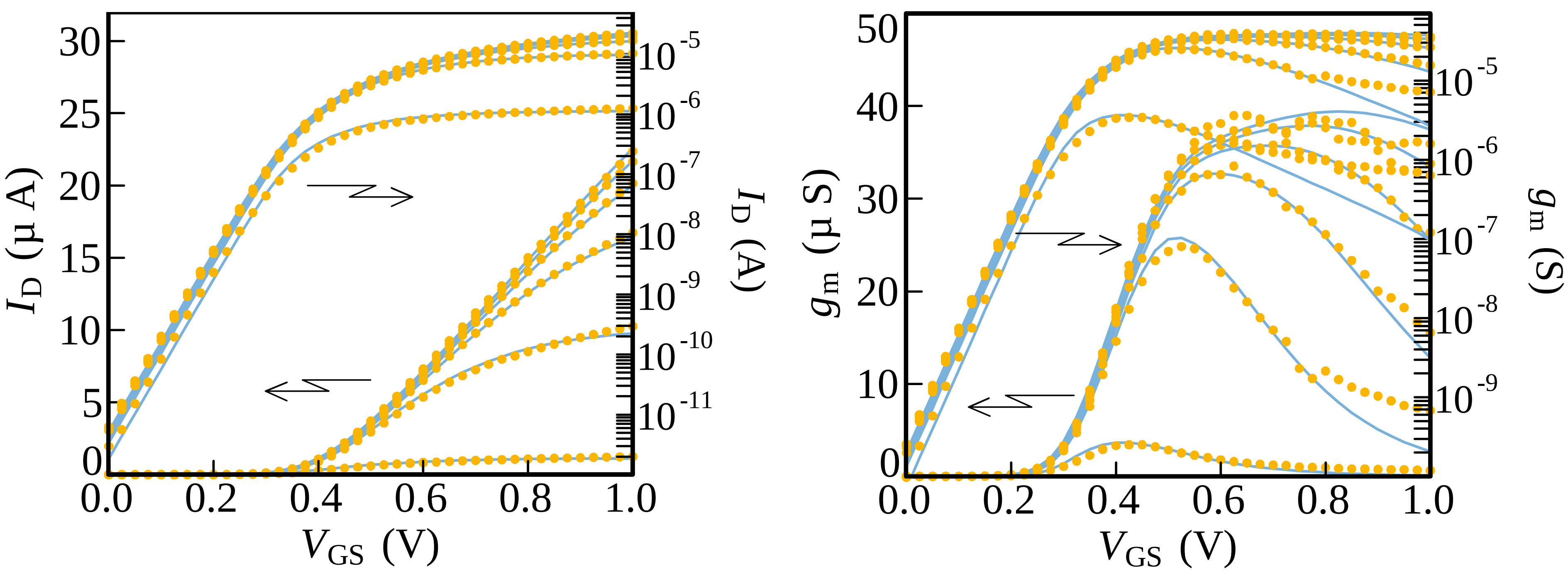
- Long-channel current and trans-conductance
  - measurements (•) vs. model (—)
  - L=1µm, t_{Si}=22nm, h_{fin}=60nm, N_{fin}=1





I-V (short channel)

- Short-channel current and trans-conductance
  - measurements (•) vs. model (—)
  - L=80nm, t_{Si}=22nm, h_{fin}=60nm, N_{fin}=1

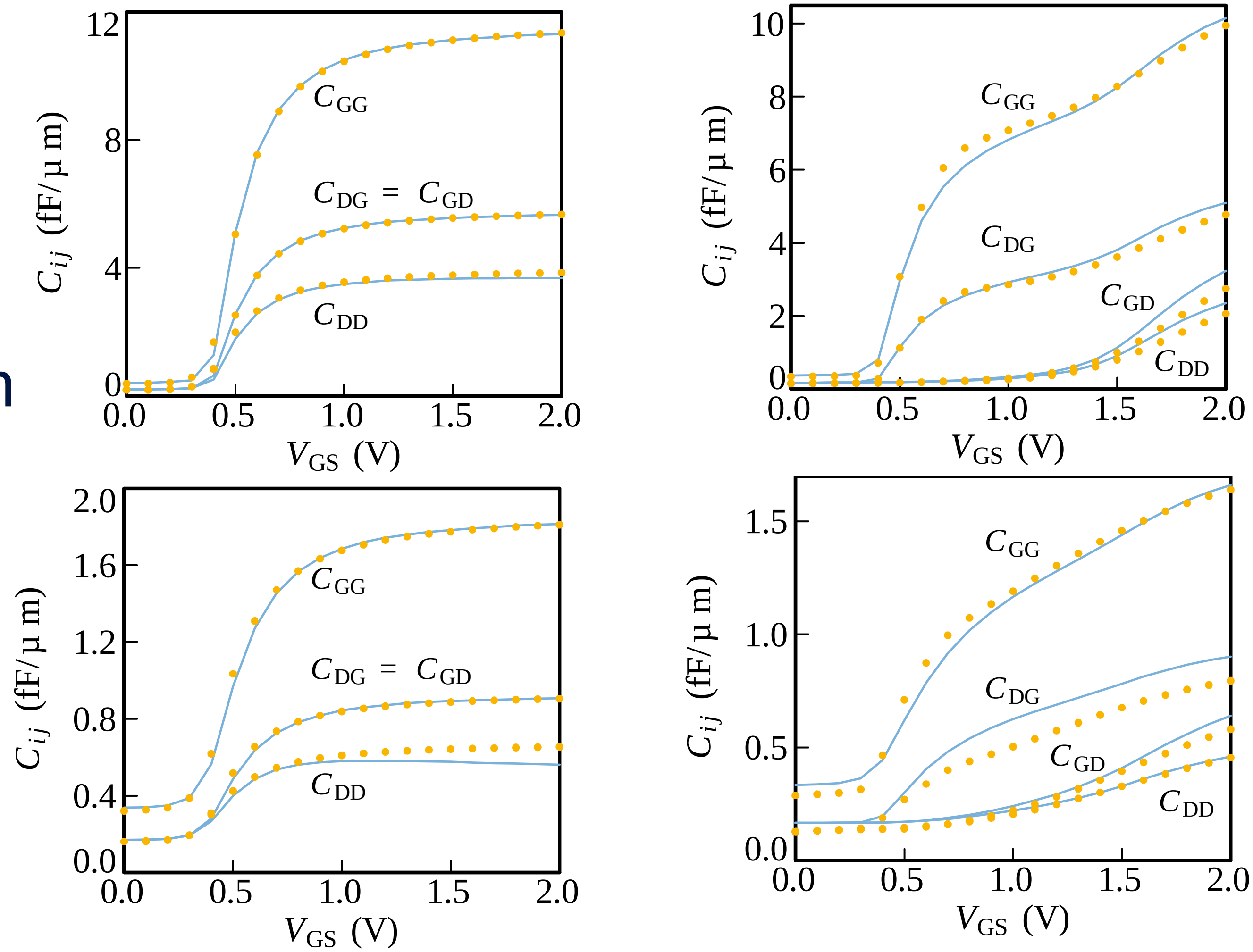


C-V and RF (long and short channel, TCAD)

TCAD (•)
model (—)
t_{Si}=10nm
t_{ox}=1.2nm

L=200nm

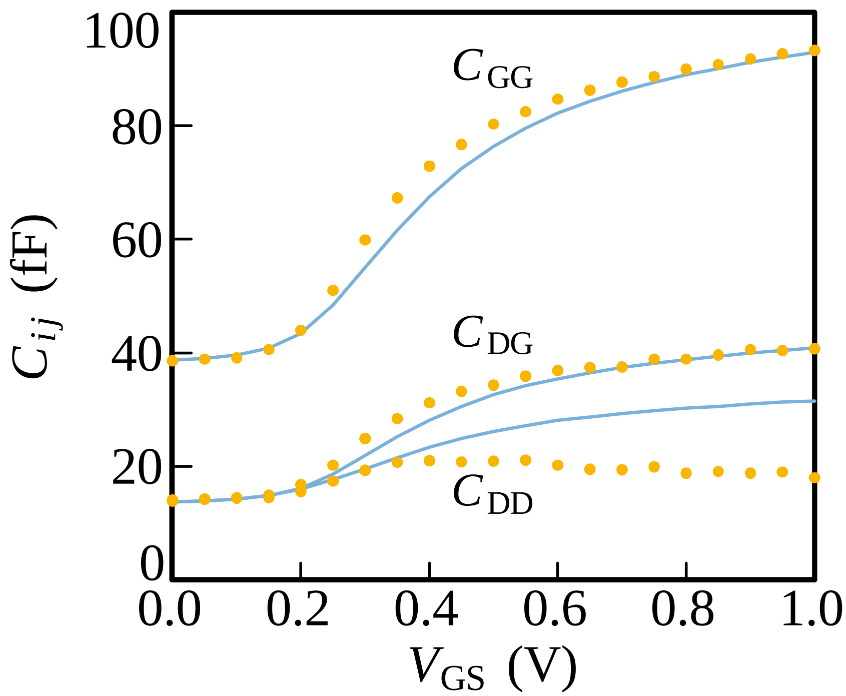
L=30nm

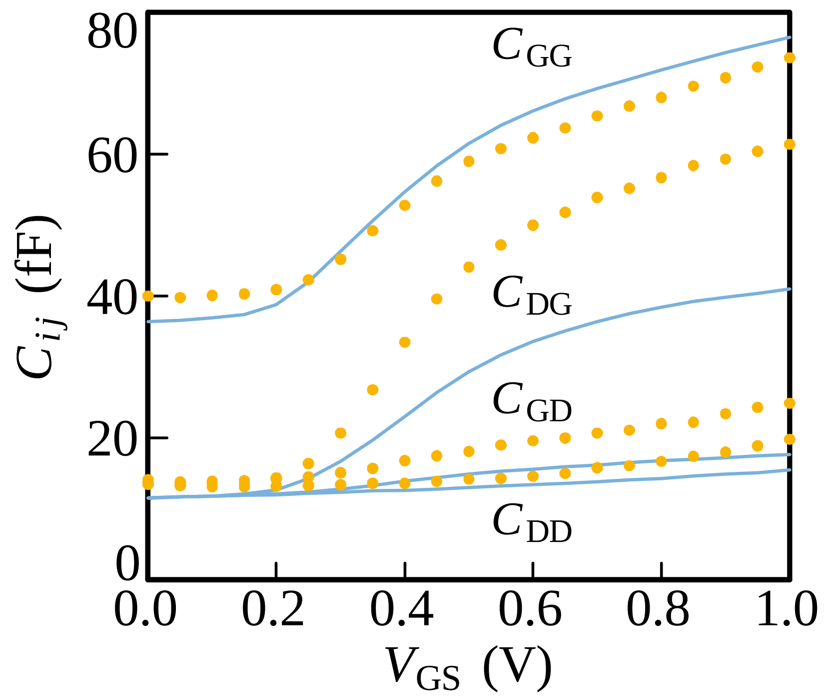


V_{DS}=0V V_{DS}=1.0V

C-V and RF (short channel, measurement)

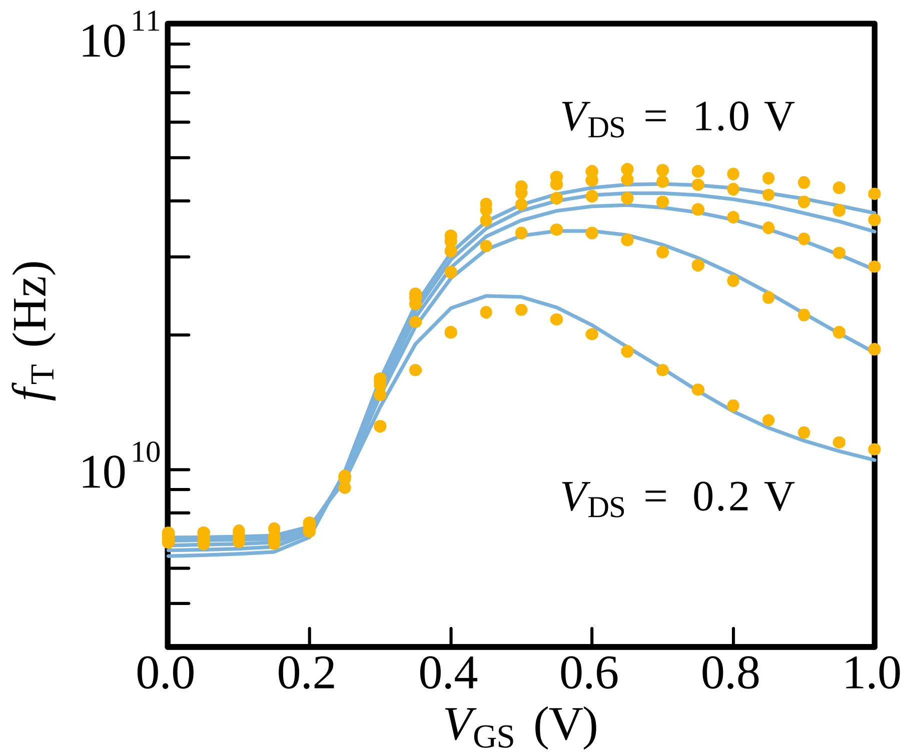
- short-channel capacitances (from S-parameter measurement at 20GHz)
  - L=110nm, t_{Si}=30nm, h_{fin}=60nm, N_{fin}=300





C-V and RF (short channel, measurement)

- cut-off frequency (from S-parameter measurement at 20GHz)
  – L=110nm, t_{Si}=30nm, h_{fin}=60nm, N_{fin}=300



Model overview (i)

- Implemented in Verilog-A
- True COMPACT model
  - no extensive numerical algorithms
- All operating regions
  - sub-threshold
  - linear/triode
  - saturation
- Suitable for all analysis types
  - dc
  - ac
  - transient
  - HB, PSS, …
- Local and global model (easy parameter extraction)

Model overview (ii)

- Used in circuit simulations
  - inverter chain
  - voltage buffers
  - differential pairs
  - …
- Physical effects included
  - field-dependent mobility
  - velocity saturation
  - conductance effects (CLM, DIBL, etc.)
  - series-resistance (bias-dependent)
  - short-channel effects
  - gate poly-depletion
  - quantum-mechanical corrections
  - overlap capacitances (ψ_s-based)
  - gate leakage current
  - geometrical scaling (L-dependence)
  - temperature dependence

Model overview (iii)

- Future additions and improvements
  - Noise
  - NQS-effects
  - Self-heating
  - Improved QM-effects
  - Improved mobility model (e.g. ballistic transport)
  - Bulk contact
  - …

Conclusion

- PSP-based FinFET model
- New model gives excellent description
  - currents (subthreshold, linear, saturation)
  - conductances
  - capacitances
- Bulk-MOSFET model (PSP) elements can be reused
- Compact, computationally efficient
- Same benefits for analog/RF applications as PSP