Compact modeling of junctionless nanowire MOSFETs

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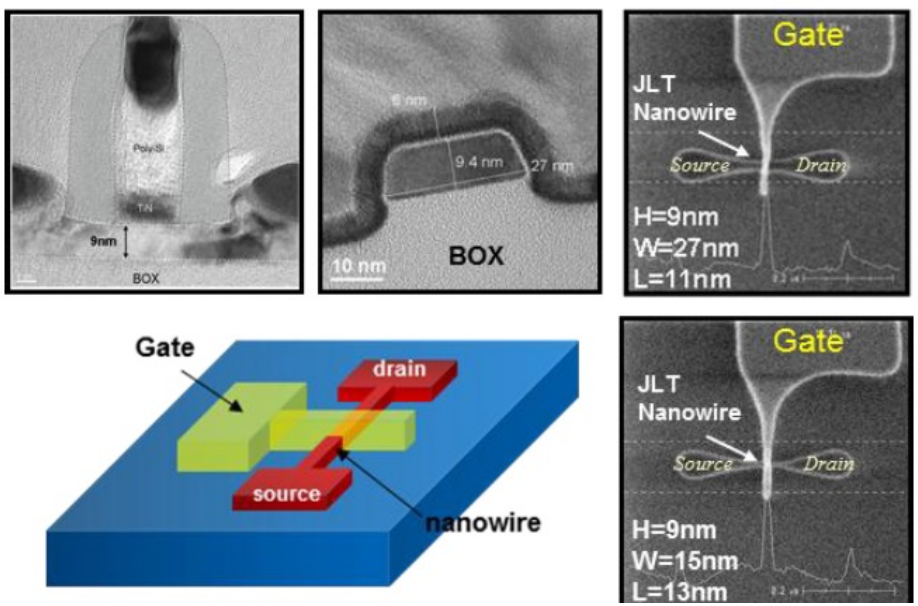
Outline

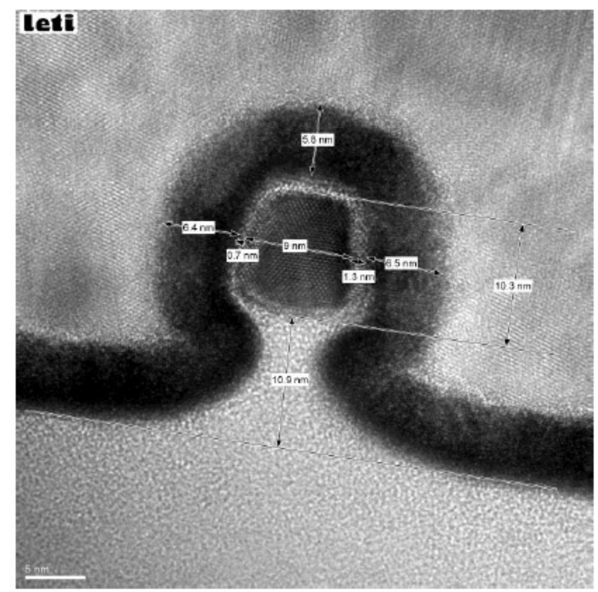
- Introduction
- Drain current and charge models in depletion
- Drain current and charge models in accumulation
- Unified drain current model
- Capacitance model
- Results
- Conclusion

Importance of the Junctionless Transistors

- Do not need source and drain junctions[1,2]
  - EASY to down-scale
  - EASY to fabricate



LETI's JLT Nanowire (FinFET)



[1] J.P. Colinge, C.W. Lee, A. Afzalian, N.D. Akhavan, R. Yan, I. Ferain *et al.*Nanowire transistors without junctionsNat Nanotechnol, 5 (2010), pp. 225–229
[2] C.W. Lee, A. Afzalian, N.D. Akhavan, R. Yan, I. Ferain, J.P. Colinge Junctionless multigate field-effect transistor Appl Phys Lett, 94 (2009), p. 053511

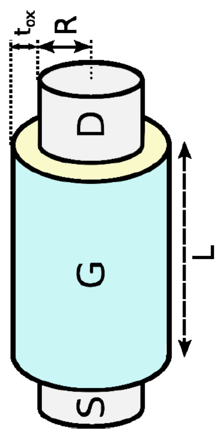
Junctionless Transistors

- Implementation in integrated circuits is NECESSARY
  - NEED of compact models adequate for circuit simulators
    - better computation speed
- Circuit design requires a complete small-signal model
  - analytical expressions of total capacitances

Junctionless SGT

- Allows excellent control of the channel charge in the Si film
- Total charges and analytical intrinsic capacitance expressions for J-SGT are presented for the first time

Schematics of a J-SGT



Simulation of a J-SGT

Electrostatic analysis

$$\frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}=\frac{qN_d}{\varepsilon_{sc}}\left(e^{\frac{\psi(r)-V}{\phi_t}}-1\right) \qquad u=r^2$$

$$u\left(\frac{\partial\psi}{\partial u}\right)^2\Bigg|_0^{R^2}+\int_0^{R^2}\left(\frac{\partial\psi}{\partial u}\right)^2 du$$

$$=\frac{qN_d\phi_t}{2\varepsilon_{sc}}\left(e^{\frac{\psi_s-V}{\phi_t}}\left(1-e^{\frac{\psi_0-\psi_s}{\phi_t}}\right)-\frac{\psi_s-\psi_0}{\phi_t}\right)$$

Parabolic potential approximation $\quad \psi(r)=\frac{\psi_s-\psi_0}{R^2}r^2+\psi_0$

This leads to:

$$v=\ln\left(\frac{Q_m}{Q_{dop}}\right)+\frac{Q_m}{C_{ox}\phi_t}-\ln\left(\frac{Q_{cp}\left[1-e^{-\frac{Q_m-Q_{dop}}{Q_{cp}}}\right]}{Q_m-Q_{dop}}\right)$$

$$Q_{cp}=\frac{2\varepsilon_{sc}\phi_t}{R} \qquad v=\frac{V_g^*+\frac{Q_{dop}}{C_{ox}}-V}{\phi_t}$$

Drain Current and Charge Models

- Depletion mode

$$\frac{V_g^* + \frac{Q_{dop}}{C_{ox}} - V}{\phi t} + \frac{Q_{dop}}{Q_{cp}} = \ln\left(\frac{Q_m}{Q_{cp}}\right) + \frac{Q_m}{Q_{eq}}$$

$$Q_{cp} = \frac{2\varepsilon_{sc}\phi_t}{R} \qquad Q_{dop} = qN_d\frac{R}{2}$$

$$Q_{eq} = \frac{Q_{cp}C_{ox}\phi_t}{Q_{cp}+C_{ox}\phi_t}$$

$$dV = -\phi t\left(\frac{1}{Q_m} + \frac{1}{Q_{eq}}\right)dQ_m$$

$$I_{dsdep} = \frac{2\pi R\mu}{L}\int_0^{V_{DS}} Q_m dV$$

$$I_{dsdep} = -\frac{2\pi R\mu}{L}\phi t\int_{Q_s}^{Q_d} Q_m\left(\frac{1}{Q_m} + \frac{1}{Q_{eq}}\right)dQ_m = \frac{2\pi R\mu}{L}\phi t\left(Q_m + \frac{Q_m^2}{2Q_{eq}}\right)\Big|_{Q_s}^{Q_d}$$

$$Q_m \approx Q_{eq}\mathrm{LW}\left(\frac{Q_{cp}}{Q_{eq}}e^{v+\frac{Q_{dop}}{Q_{cp}}}\right)$$

Drain Current and Charge Models

- Depletion mode

$$Q_{totdep} = -2\pi R\int_0^L Q_m\,dx = -(2\pi R)^2 \frac{\mu}{I_{dsdep}} \int_0^{V_{DS}} Q_m^2\,dV$$

$$Q_{cp} = \frac{2\varepsilon_{sc}\phi_t}{R} \qquad Q_{dop} = qN_d\frac{R}{2}$$

$$Q_{eq} = \frac{Q_{cp}C_{ox}\phi_t}{Q_{cp}+C_{ox}\phi_t}$$

$$Q_{totdep} = (2\pi R)^2 \frac{\mu}{I_{dsdep}} \phi t\left(\frac{Q_m^2}{2} + \frac{Q_m^3}{3Q_{eq}}\right)\Bigg|_{Q_s}^{Q_d}$$

$$Q_m \approx Q_{eq}\mathrm{LW}\left(\frac{Q_{cp}}{Q_{eq}}e^{v+\frac{Q_{dop}}{Q_{cp}}}\right)$$

$$Q_{Ddep} = -2\pi R\int_0^L \frac{x}{L}Q_m\,dx = \frac{-(2\pi R)^3\mu^2\phi t^2}{LI_{dsdep}^2}\int_{Q_s}^{Q_d} Q_m^2\left(Q_m - Q_s + \frac{Q_m^2 - Q_s^2}{2Q_{eq}}\right)\cdot\left(\frac{1}{Q_m}+\frac{1}{Q_{eq}}\right)dQ_m$$

$$Q_{Sdep} = Q_{totdep} - Q_{Ddep}$$

Drain Current and Charge Models

- Accumulation Mode

$$\frac{V_g^* + \frac{Q_{dop}}{C_{ox}} - V}{\phi t} = \ln\left(\frac{Q_m^2}{Q_{dop}Q_{cp}}\right) + \frac{Q_m}{C_{ox}\phi t}$$

$$dV = -\phi t\left(\frac{2}{Q_m} + \frac{1}{C_{ox}\phi t}\right)dQ_m$$

$$I_{dsacc} = -\frac{2\pi R\mu}{L}\phi t\left(2Q_m + \frac{Q_m^2}{2C_{ox}\phi t}\right)\Bigg|_{Q_s}^{Q_d}$$

$$Q_m \approx 2C_{ox}\phi_t \mathrm{LW}\left(\frac{\sqrt{Q_{cp}Q_{dop}}}{2C_{ox}\phi_t}e^{\frac{v}{2}}\right)$$

Drain Current and Charge Models

- Accumulation Mode

$$Q_{totacc} = (2\pi R)^2 \frac{\mu}{I_{dsacc}} \phi t \left(Q_m^2 + \frac{Q_m^3}{3C_{ox}\phi t} \right) \Bigg|_{Q_s}^{Q_d}$$

$$Q_{Dacc} = -2\pi R \int_0^L \frac{x}{L} Q_m dx = \frac{-(2\pi R)^3 \mu^2 \phi t^2}{L I_{dsacc}^2} \int_{Q_s}^{Q_d} Q_m^2 \left(2(Q_m - Q_s) + \frac{Q_m^2 - Q_s^2}{2C_{ox}\phi t} \right) \cdot \left(\frac{2}{Q_m} + \frac{1}{C_{ox}\phi t} \right) dQ_m$$

$$Q_m \approx 2C_{ox}\phi_t LW \left(\frac{\sqrt{Q_{cp}Q_{dop}}}{2C_{ox}\phi_t} e^{\frac{v}{2}} \right)$$

$$Q_{Sacc} = Q_{totacc} - Q_{Dacc}$$

Unified Drain Current Model

- An approximate solution of:

$$v = \ln\left(\frac{Q_m}{Q_{dop}}\right) + \frac{Q_m}{C_{ox}\phi_t} - \ln\left(\frac{Q_{cp}\left[1 - e^{-\frac{Q_m - Q_{dop}}{Q_{cp}}}\right]}{Q_m - Q_{dop}}\right)$$

$$Q_{eq} = \frac{Q_{cp}C_{ox}\phi_t}{Q_{cp}+C_{ox}\phi_t}$$

$$Q_m = C_{ox}\phi_t \mathrm{LW}\left(\frac{Q_{dop}Q_{cp}}{C_{ox}\phi_t}\frac{1 - e^{\frac{Q_{dop} - Q_m^a}{Q_{cp}}}}{Q_m^a - Q_{dop}}e^{v}\right)$$

$$Q_m^a = Q_{eq}\mathrm{LW}\left(\frac{Q_{dop}Q_{cp}}{Q_{eq}}\frac{e^{\frac{Q_m^{a0}}{Q_{cp}}} - e^{\frac{Q_{dop}}{Q_{cp}}}}{Q_m^{a0} - Q_{dop}}e^{v}\right) \qquad v = \frac{V_{gs} - V_{FB} + \frac{Q_{dop}}{C_{ox}} - V}{\phi_t}$$

Unified Drain Current Model

$$I_{ds} = 2\pi\frac{R}{L}\mu\phi_t\left(f\left(Q_m(0)\right) - f\left(Q_m(V_{ds})\right)\right)$$

$$f(Q) = \frac{Q^2}{2Q_{eq}} + 2Q - AQ\ln\left(1 + e^{\frac{Q-Q_{dop}}{2AQ_{cp}}}\right) + Q_{dop}\ln\left(\frac{Q - Q_{dop}}{2Q_{cp}\left(e^{\frac{Q-Q_{dop}}{2Q_{cp}}} - 1\right)}\right)$$

With A=1,425

Intrinsic Capacitance Model

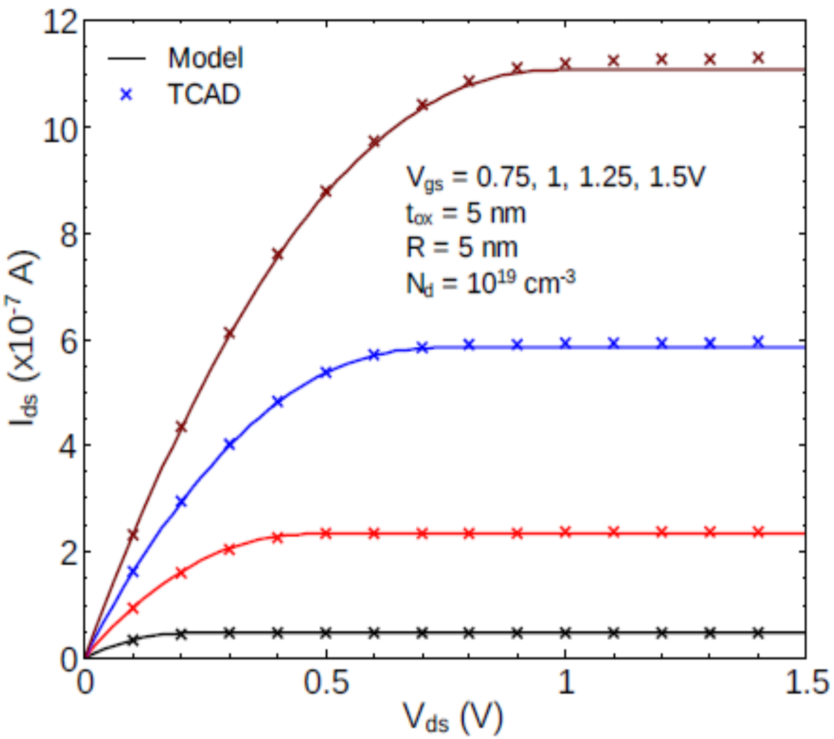
$$C_{ijdep/acc} = -\frac{\partial Q_{idep/acc}}{\partial V_j} = -\frac{\partial Q_{idep/acc}}{\partial Q_j} \cdot \frac{\partial Q_j}{\partial V_j} \quad i \neq j$$

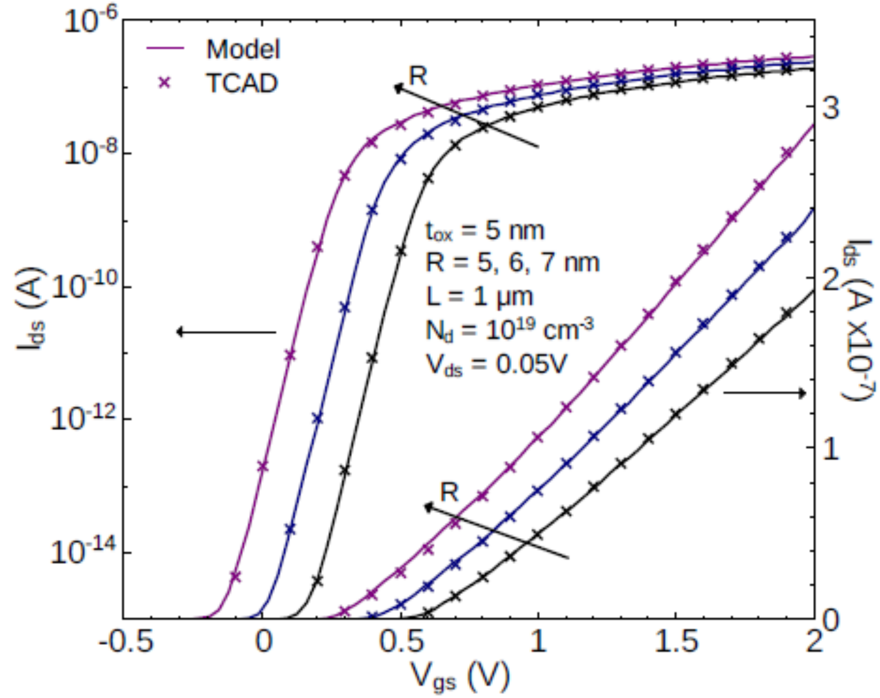
$$C_{ijdep/acc} = \frac{\partial Q_{idep/acc}}{\partial V_j} = \frac{\partial Q_{idep/acc}}{\partial Q_j} \cdot \frac{\partial Q_j}{\partial V_j} \quad i = j$$

- The complete capacitance model = sum of capacitances in depletion and accumulation modes sewed together by a *tanh* function

$$C_{ij} = C_{ijdep}\left(\frac{1-\tanh\left[\left(V_g^* + q1\right)q2\right]}{2}\right) + C_{ijacc}\left(\frac{1-\tanh\left[\left(V_g^* + q1\right)q2\right]}{2}\right)$$

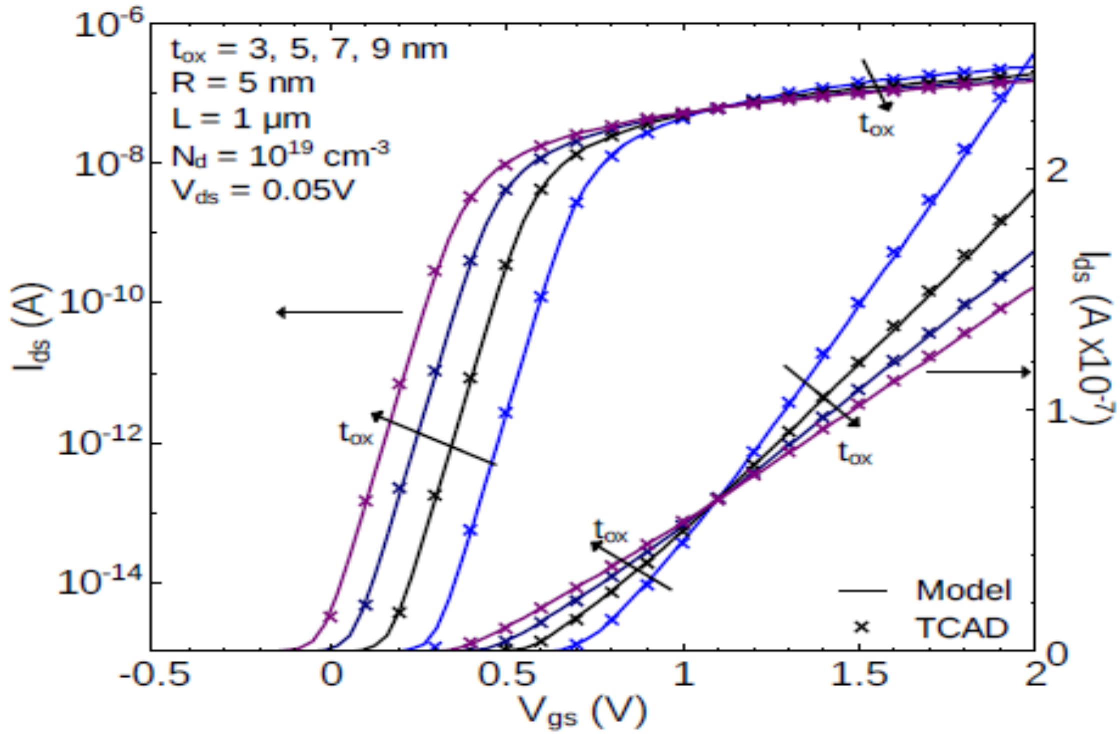
ATLAS simulations vs MODEL





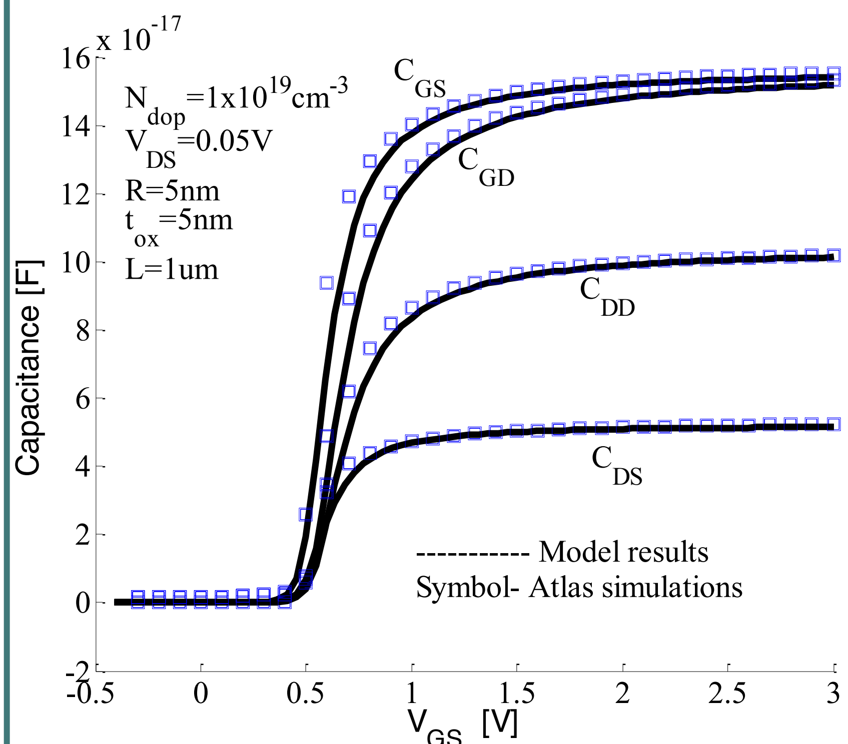
Comparison of the modeled I-V characteristics with TCAD simulations

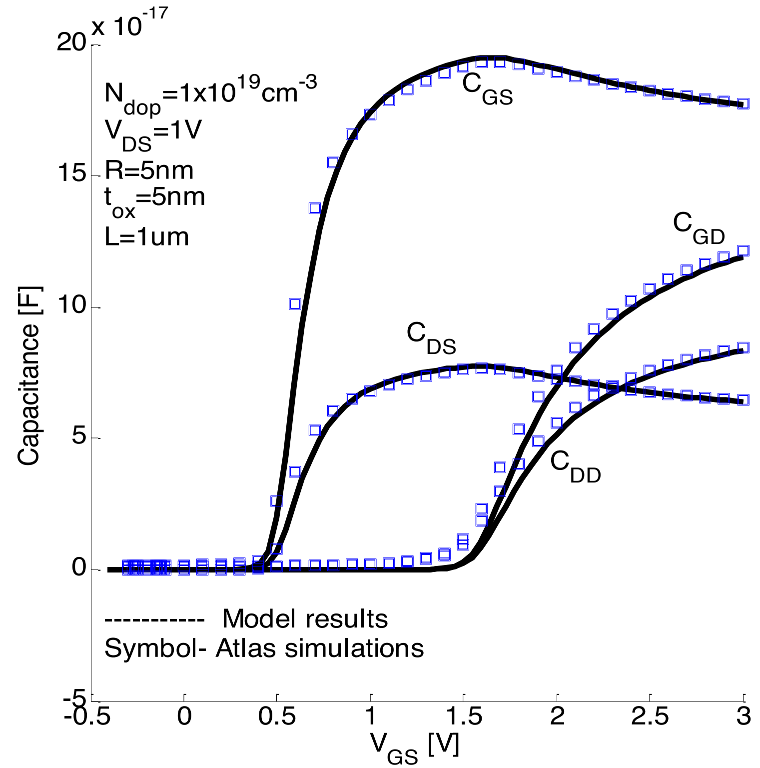
ATLAS simulations vs MODEL



Comparison of the modeled I-V characteristics with TCAD simulations for different values of the gate oxide

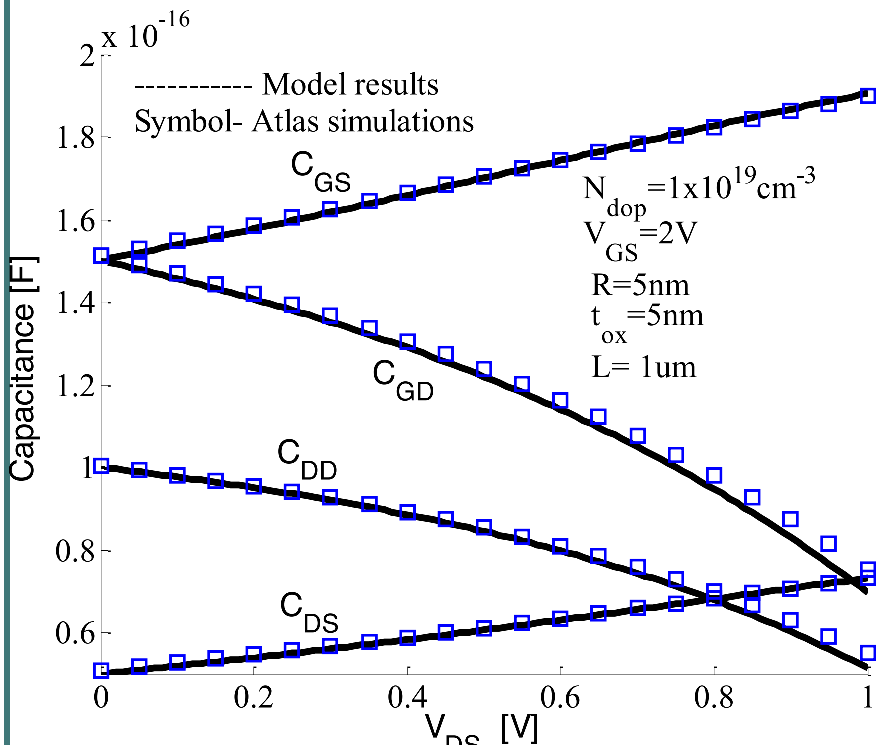
ATLAS simulations vs MODEL

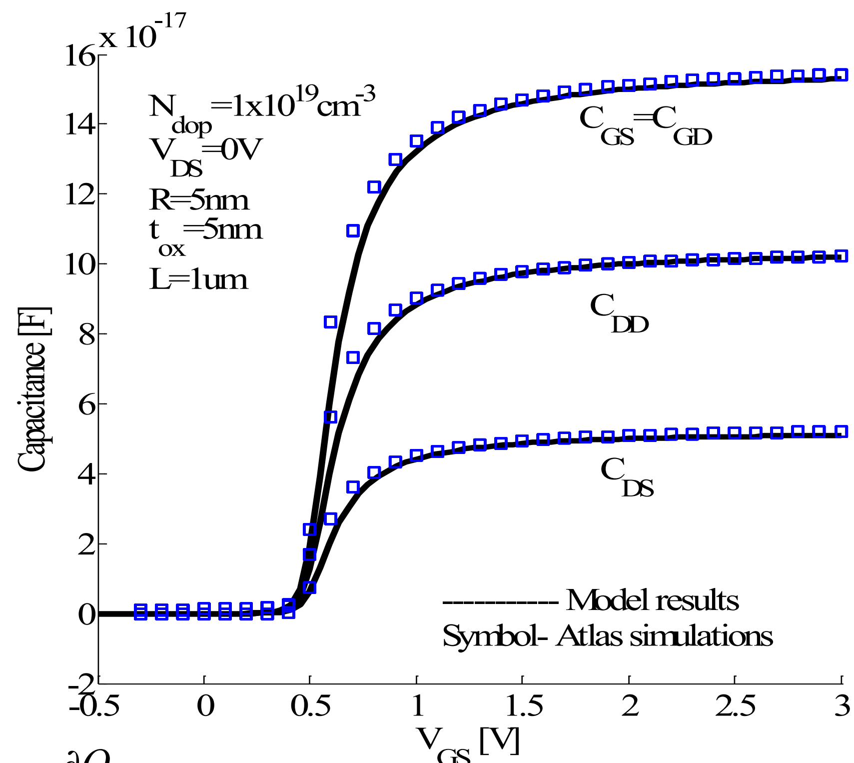




By computing four out of the nine possible intrinsic capacitances we can, afterwards, calculate the other five

ATLAS simulations vs MODEL



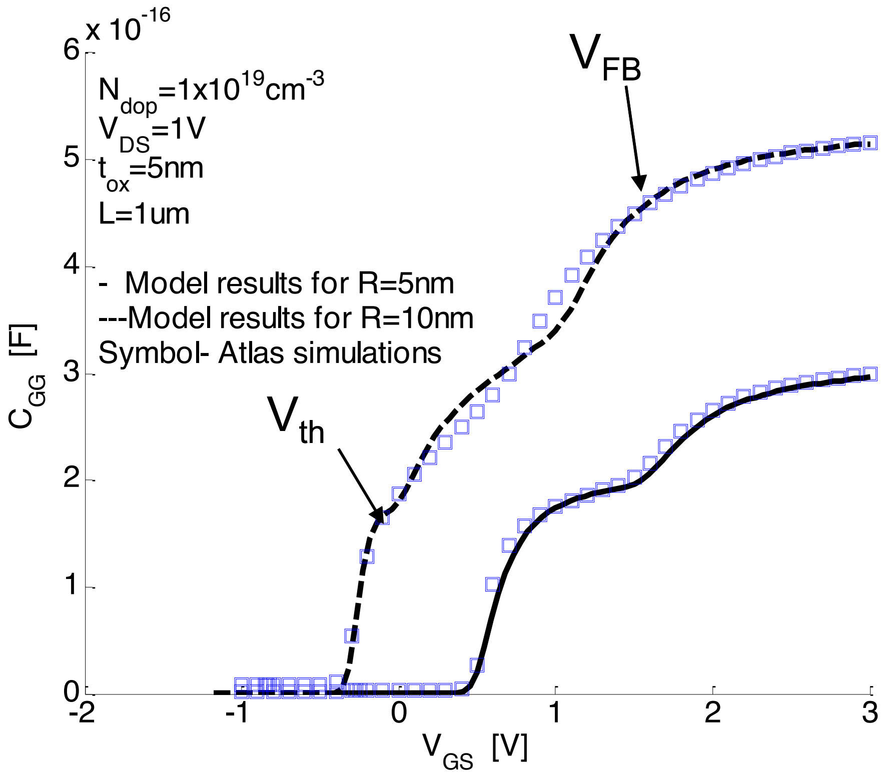


$$C_{gg} = -2\pi RL \frac{\partial Q_d}{\partial V_d}$$

0/0 Instability

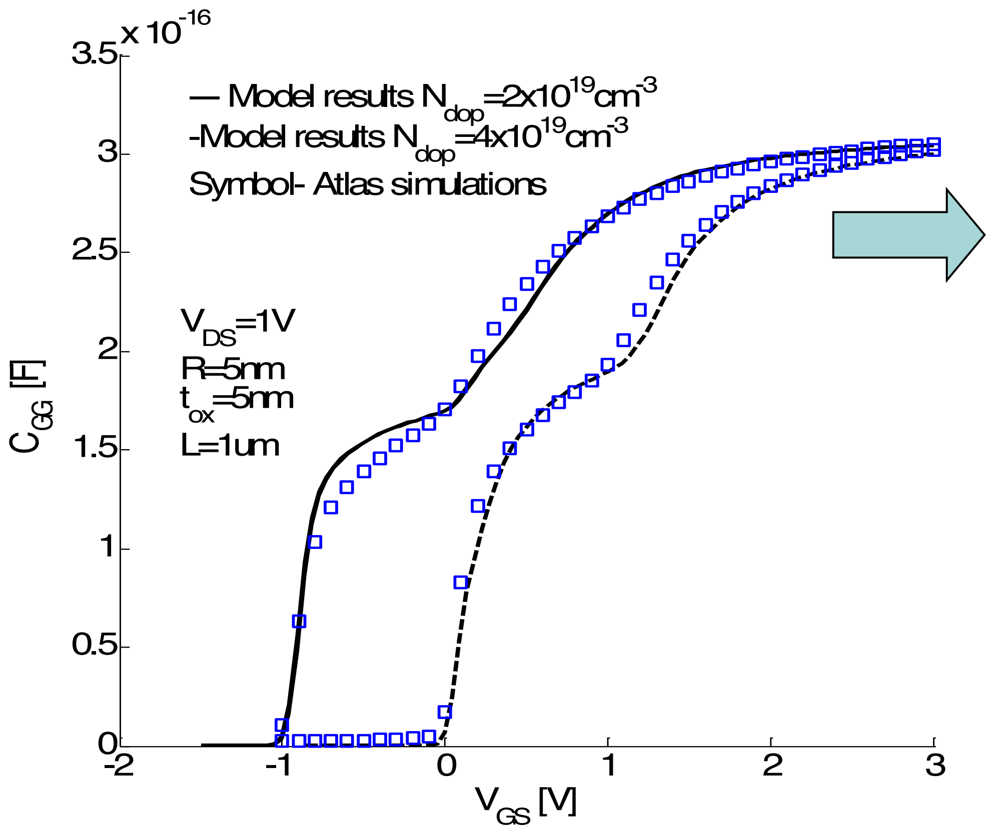
$$C_{gg} = 2C_{GS} = 2C_{GD} = 2C_{SG} = 2C_{DG} = 3C_{SS} = 3C_{DD} = -6C_{SD} = -6C_{DS}$$

$C_{GG} = C_{GS} + C_{GD}$ for R=5nm and R=10nm



- R=5nm–no ‘distorsions’
- similar capacitance curve as for inversion transistors
- R=10nm – see ‘distorsions’

C_{GG} for different N_{dop}



As V_{th} becomes more negative, the transition part becomes more visible

Which is the optimum Si thickness versus doping combination???

Advantages of our model

- Explicit and anlaytic
- Very simple and easy to implement
- Reproduces well the two different conduction modes: accumulation & depletion
- Good agreement with 3D numerical simulations
- Some limitations, but not regarding a real device

Thank you for your attention!