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# A Carrier-Based Analytic Model for Undoped Surrounding-Gate MOSFETs

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**WCM'2006 Boston, USA**





## Non-Classic CMOS: A Promise for CMOS Limit

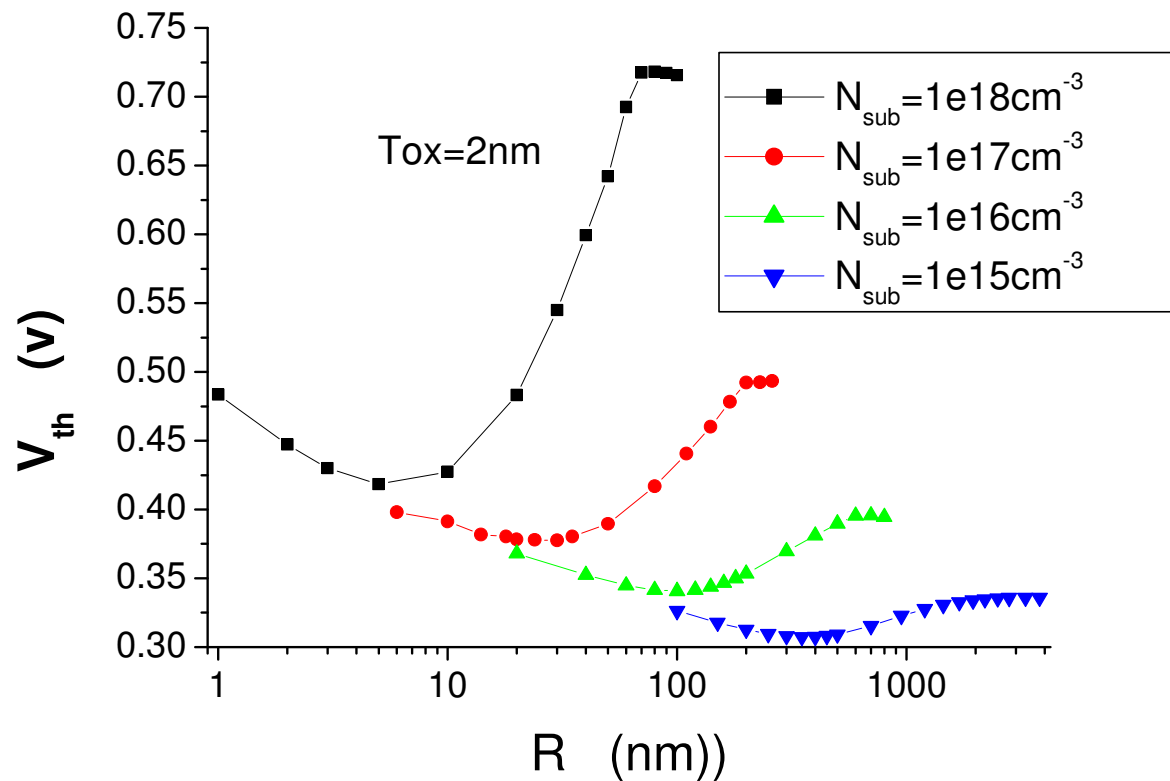
- ❑ Excellent Scaling Characteristic
- ❑ Low sub-threshold leakage
- ❑ High drive current
- ❑ Low parasitic effect
- ❑ High integration density





# Challenges of Non-Classical Device Modeling

## Complex $V_{th}$ behavior



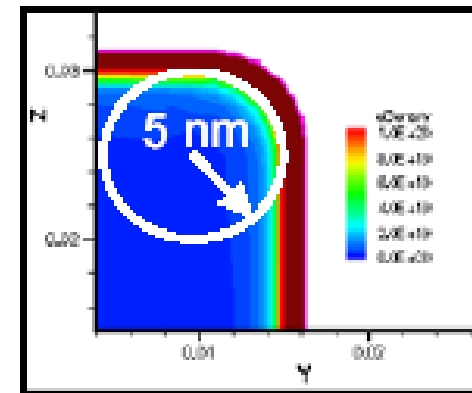
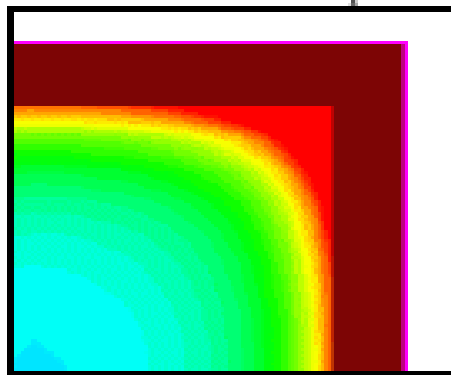
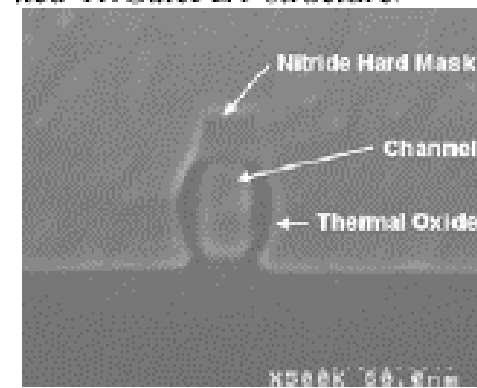
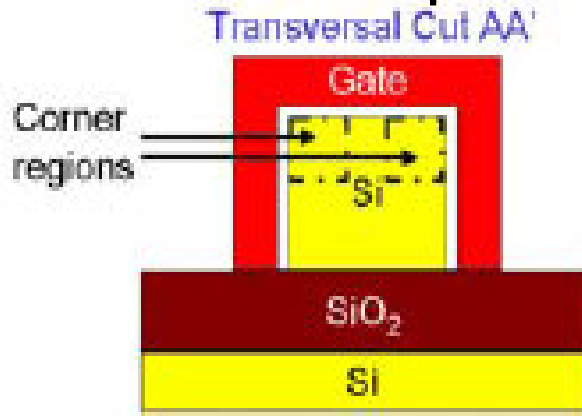


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# Challenges of Non-Classical CMOS Modeling

## Complex shape---Corner effect

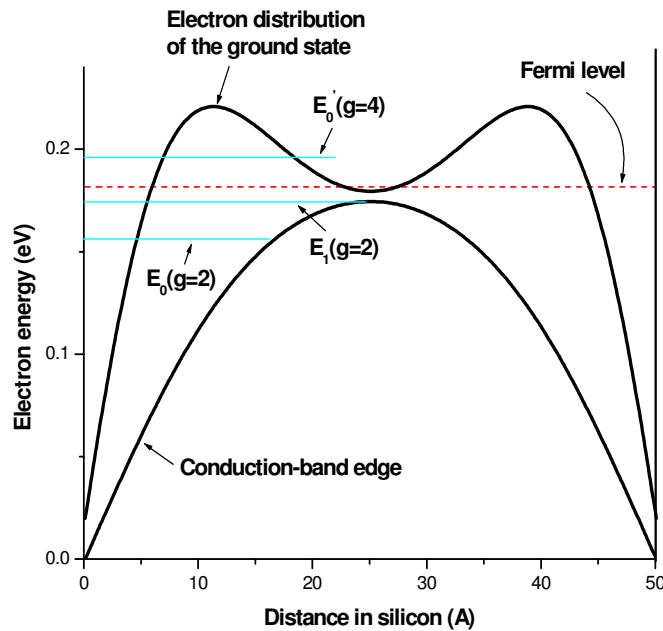




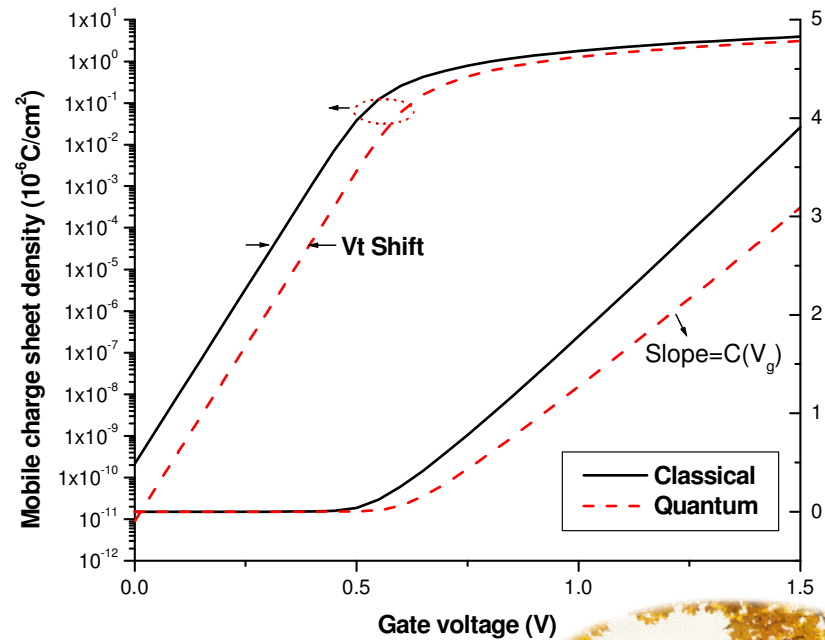
# Challenges of Non-Classical Device Modeling

## Quantum-Mechanic effect(1-D, 2-D)

The physical picture



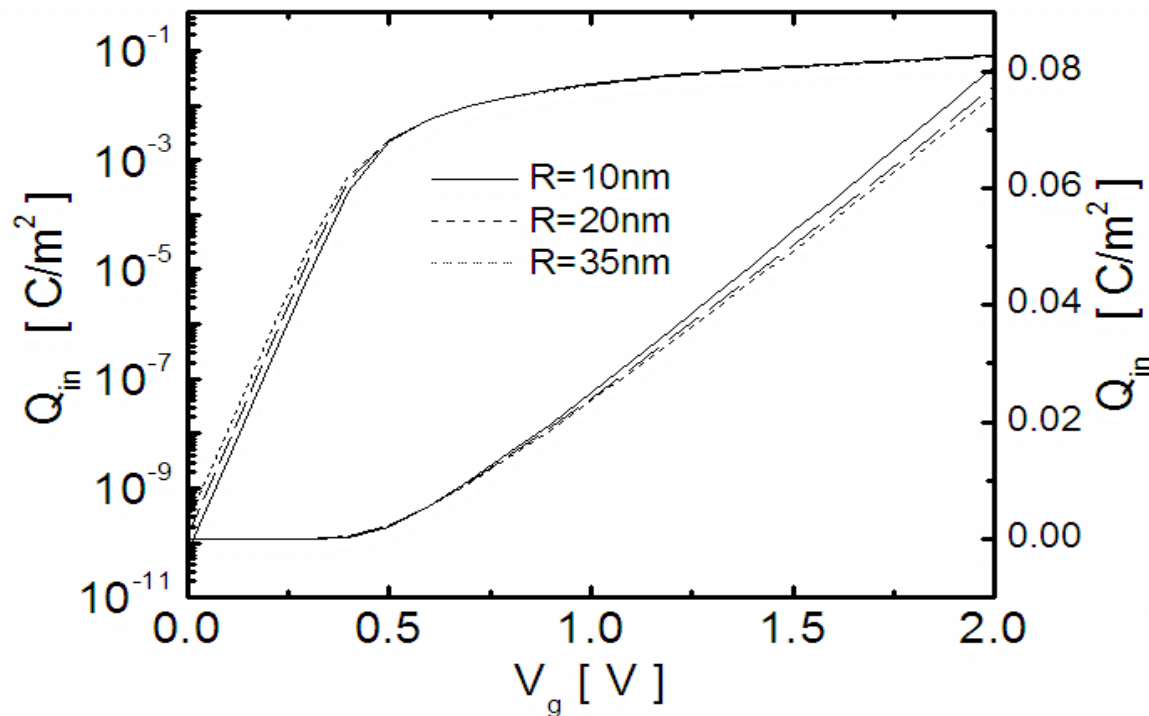
QM effect on I-V characteristics





# Challenges of Non-Classical Device Modeling

## Volume inversion effect







## Carrier-Based SRG Model ( Basic device physics)

$$I_{ds} = \mu w C_{ox} \left( \frac{kT}{q} \right)^2 q_{in} \frac{d\phi_{fn}}{dy}$$
$$\frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = \frac{kT}{qL_i^2} \exp \left[ \frac{q(\phi - \phi_{fn})}{kT} \right]$$
$$n = n_i \exp \left( \frac{q(\phi - \phi_{fn})}{kT} \right)$$
$$V_G - \Delta\phi_i = \phi_S + E_{ox} t_{oxeff} = \phi_s + \frac{Q_{in}}{\epsilon_{ox}} t_{oxeff}$$





## Carrier-Based SRG Model ( Model derivation)

$$\theta = k - 2 \ln [1 - \alpha r^2]$$

### Boundary Conditions

$$\left. \frac{d\phi}{dr} \right|_{r=0} = 0 \quad \phi \Big|_{r=0} = \phi_0$$

### Poisson's equation

$$\phi(r) = \phi_0 - \frac{2kT}{q} \ln \left[ 1 - \frac{r^2}{8L_i^2} \exp \left[ \frac{q(\phi_0 - V_{ch})}{kT} \right] \right]$$





## Carrier-Based SRG Model ( Model derivation)

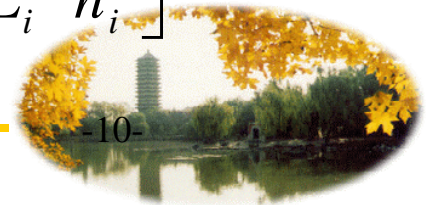
$$\phi(r) = \phi_0 - \frac{2kT}{q} \ln \left[ 1 - \frac{r^2}{8L_i^2} \exp \left[ \frac{q(\phi_0 - V_{ch})}{kT} \right] \right]$$

### Boltzmann statistics

$$n = n_i \exp \left( \frac{q(\phi - V_{ch})}{kT} \right) \quad n_0 = n_i \exp \left( \frac{q(\phi_0 - V_{ch})}{kT} \right)$$

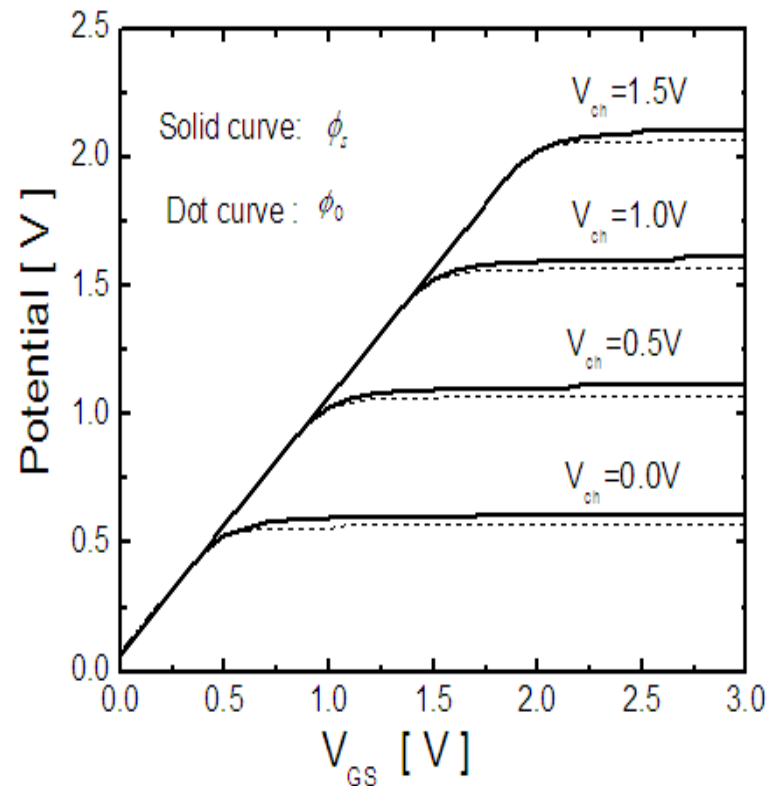
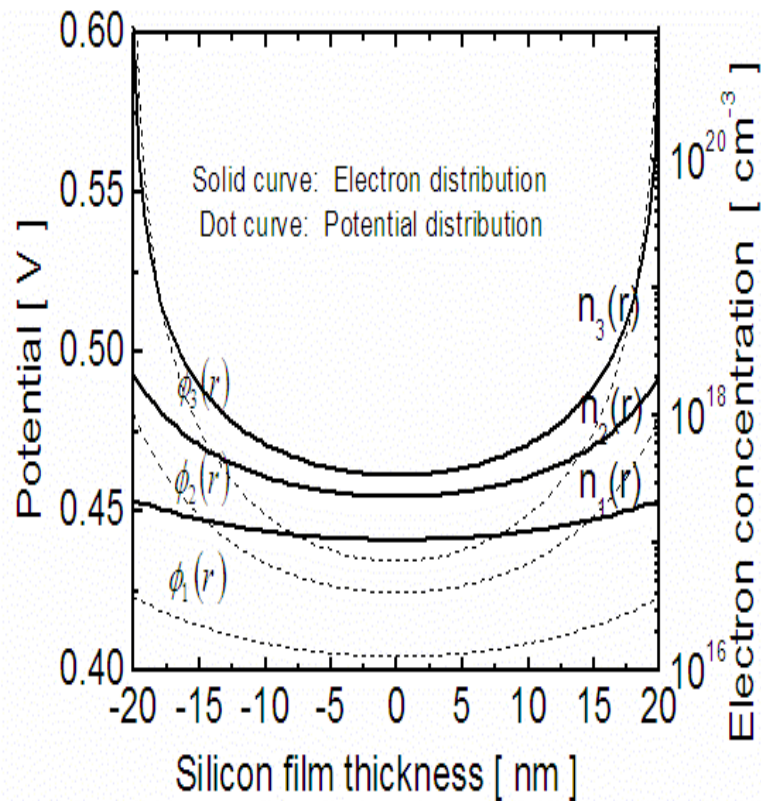
### Carrier-based potential solution

$$\phi(r) = V_{ch} + \frac{kT}{q} \ln \left[ \frac{n_0}{n_i} \right] - \frac{2kT}{q} \ln \left[ 1 - \frac{r^2}{8L_i^2} \frac{n_0}{n_i} \right]$$



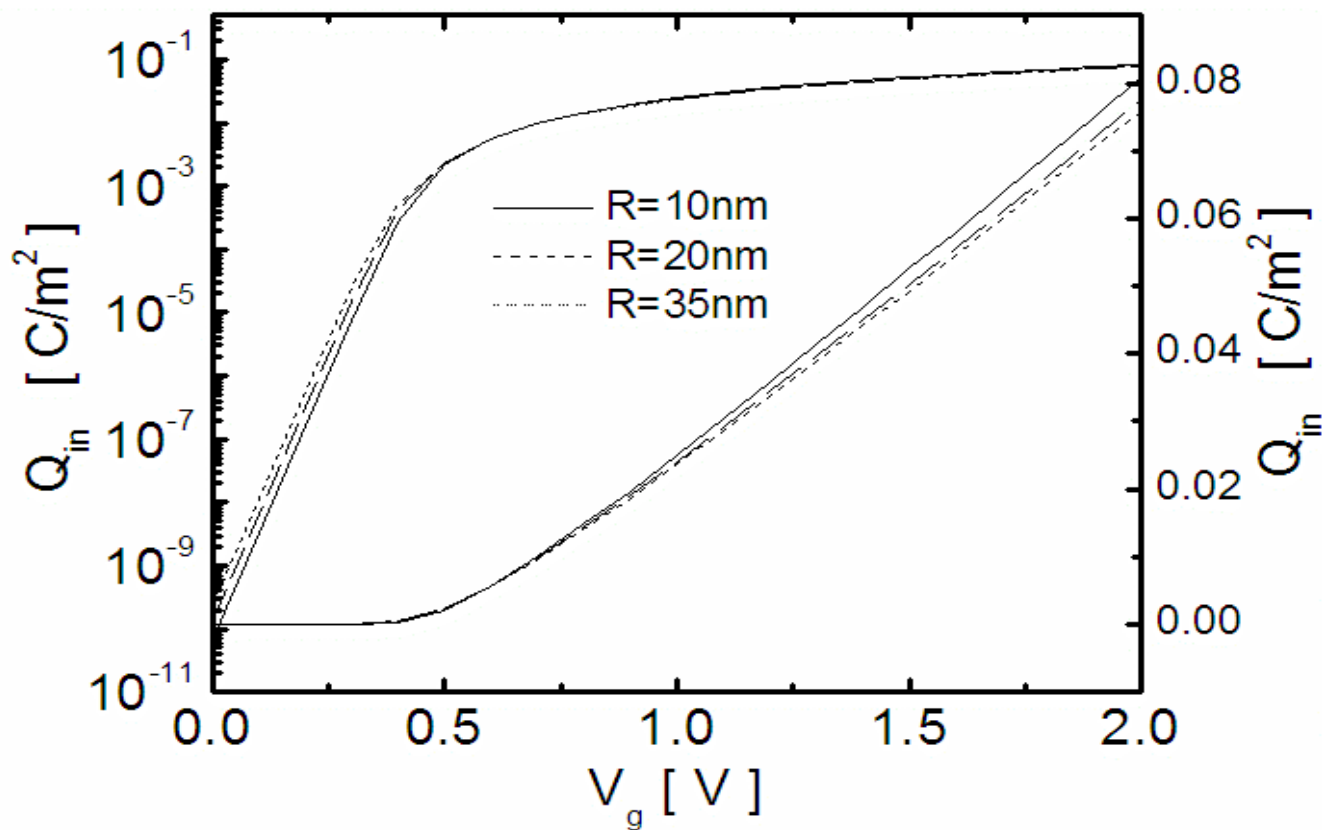


# Carrier-Based SRG Model ( potential and electron distribution )





# Carrier-Based SRG Model ( Volume inversion)





## Carrier-Based SRG Model ( I-V Model)

Analytic current formulation

$$I_{ds} = \mu \frac{2\pi\epsilon_{si}}{L} \left( \frac{2kT}{q} \right)^2 F[n_{0s}, n_{od}]$$

where

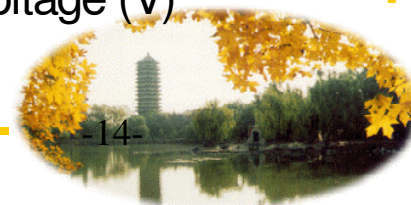
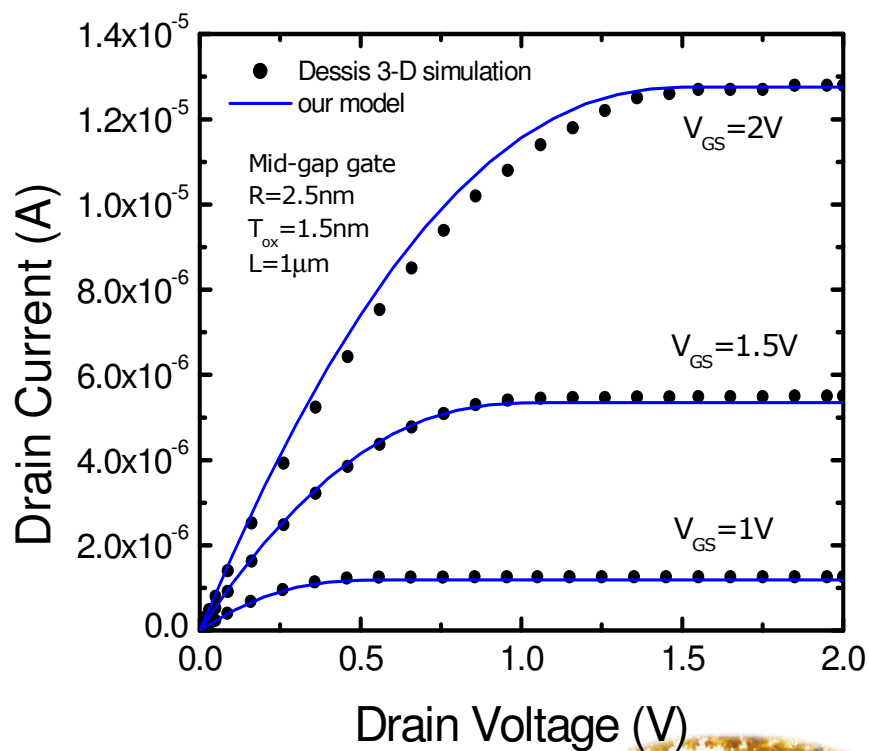
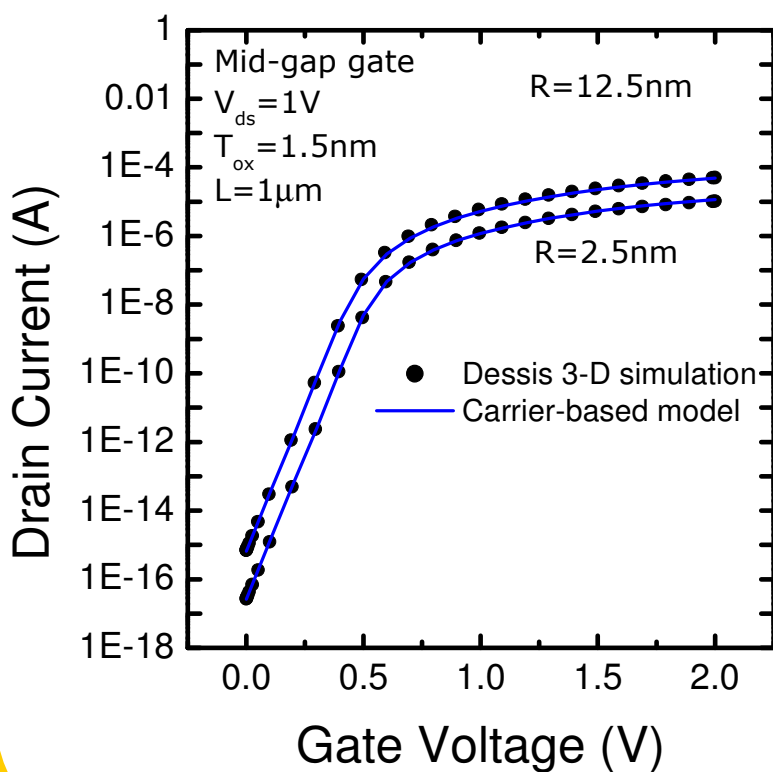
$$F[n_{0s}, n_{od}] = \left[ \ln \left[ 1 - \frac{R^2}{8L_i^2} \frac{n_0}{n_i} \right] + \frac{2 \left[ \epsilon_{ox} - 2\epsilon_{si} \ln \left( 1 + \frac{t_{ox}}{R} \right) \right]}{\epsilon_{ox} \left[ 1 - \frac{R^2}{8L_i^2} \frac{n_0}{n_i} \right]} + \frac{2\epsilon_{si} \ln \left( 1 + \frac{t_{ox}}{R} \right)}{\epsilon_{ox} \left[ 1 - \frac{R^2}{8L_i^2} \frac{n_0}{n_i} \right]^2} \right] \left| \begin{matrix} n_{0s} \\ n_{0D} \end{matrix} \right.$$





# Carrier-Based SRG Model

## ( Comparison of model and simulation )





# Carrier-Based SRG Model ( Conductance Model)

**Analytic output-conductance**

$$G_{ds} = \left. \frac{\partial I_{ds}}{\partial V_{ds}} \right|_{V_{gs}} = \frac{\mu \varepsilon_{si} \pi R^2 kT}{L q L_i^2} \frac{n_{0d}}{n_i} \left[ 1 - \frac{R^2}{8 L_i^2} \frac{n_{0d}}{n_i} \right]$$

**Analytic trans-conductance**

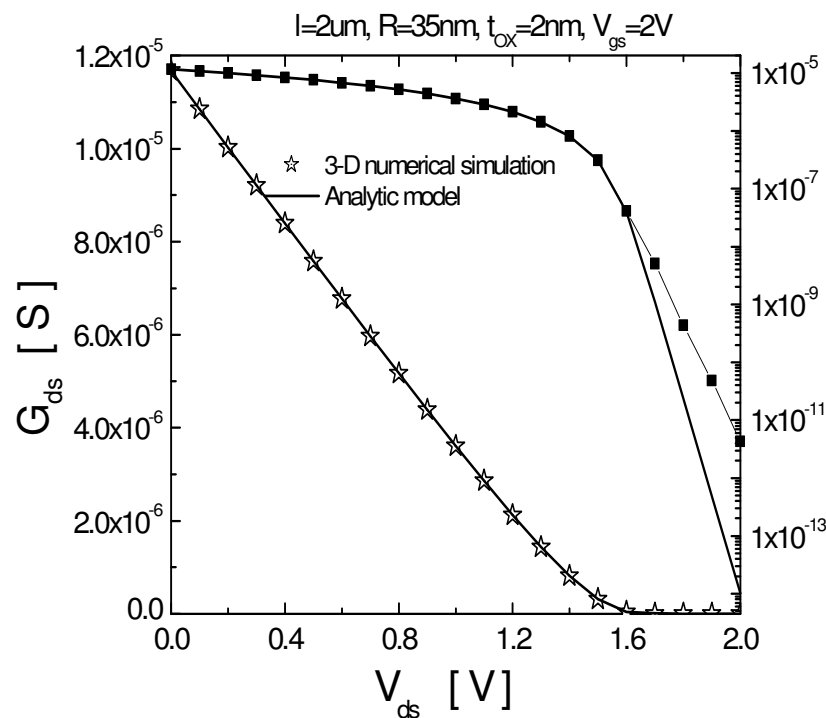
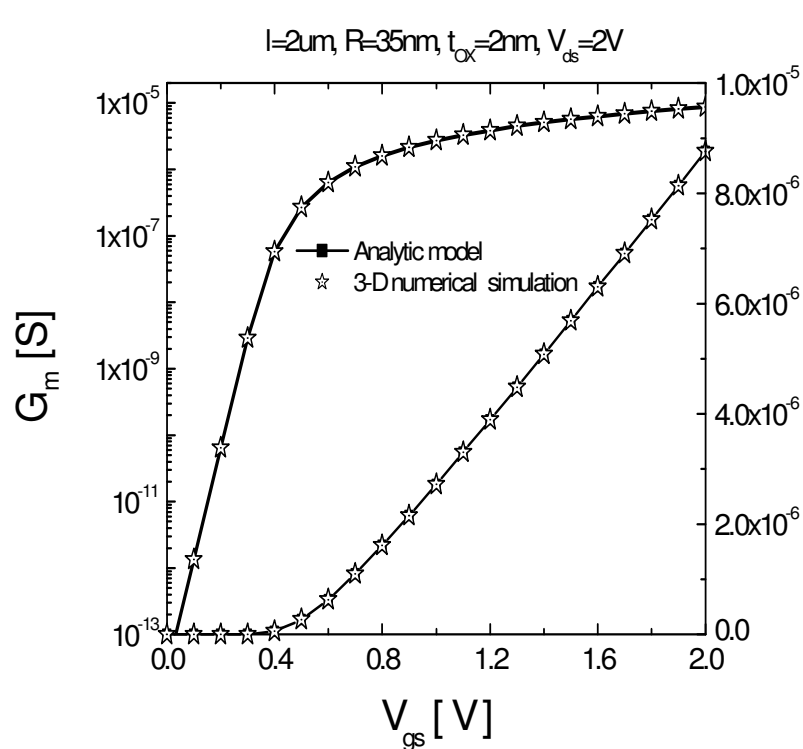
$$G_m = \frac{\mu \varepsilon_{si} \pi R^2 kT}{L q L_i^2} \left[ \frac{\frac{n_{0s}}{n_i}}{\left( 1 - \frac{R^2}{8 L_i^2} \frac{n_{0s}}{n_i} \right)} - \frac{\frac{n_{0d}}{n_i}}{\left( 1 - \frac{R^2}{8 L_i^2} \frac{n_{0d}}{n_i} \right)} \right]$$





# Carrier-Based SRG Model

## ( Comparison of model and simulation )





## Summary

- ❑ Many challenges for non-classical CMOS modeling
- ❑ Carrier-based theory is a good first step for MG modeling
- ❑ Unified model theory dream for bulk and non-classical
- ❑ Good research topics for doping, QME of SRG

