BDMC Winter Webinar

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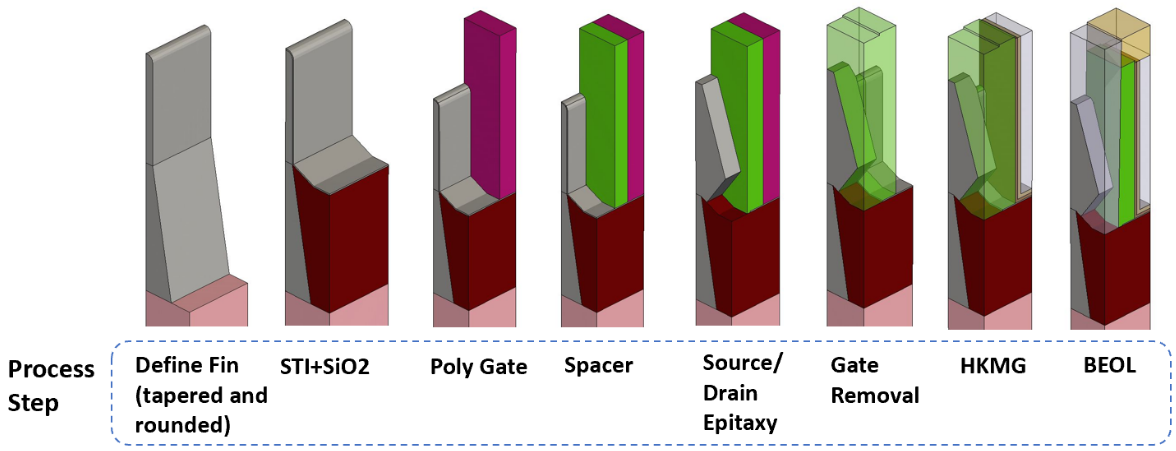
Mar. 19, 2020

Part I
Scaling of NC-FinFETs

Motivation

- Study the scalability of FinFETs within IRDS Device Constrains

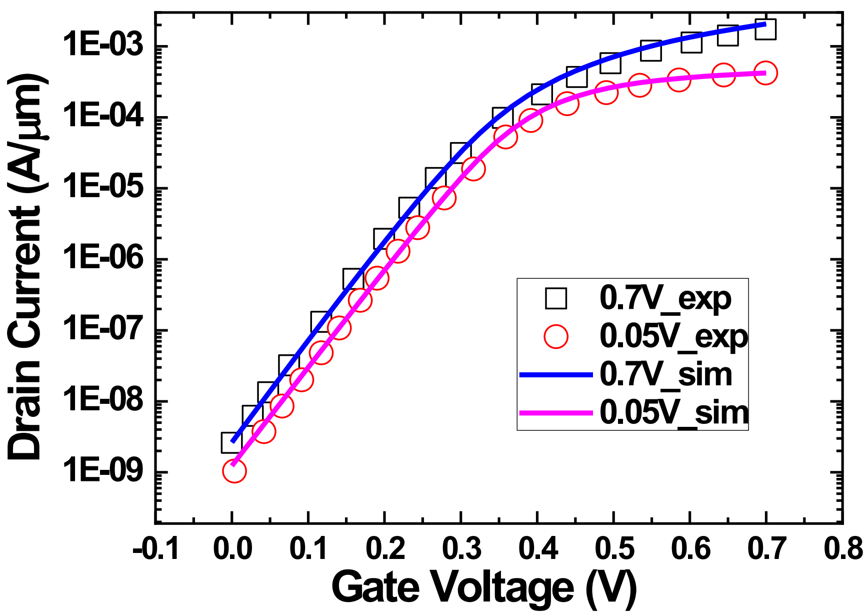
Step 1: Build the Device using TCAD

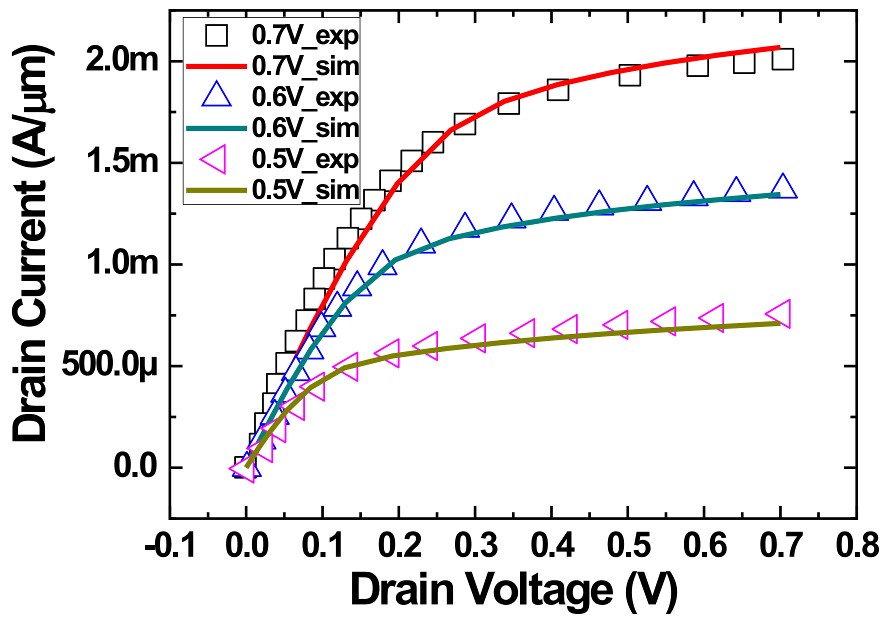


Node Labeling (nm)	"5"
Year of Production	**2020**
Gate Length (nm) -HP	**18**
VDD (V)	**0.70**
Cch (fF/um) - HP	**0.45**
Ion (uA/um) at Ioff=10 (nA/um)	**0.85**

Step 2: Calibrate TCAD Mobility and Series Resistance to match Intel Lg=18nm[1]

[1]C. Auth, et. al., IEDM, 2017

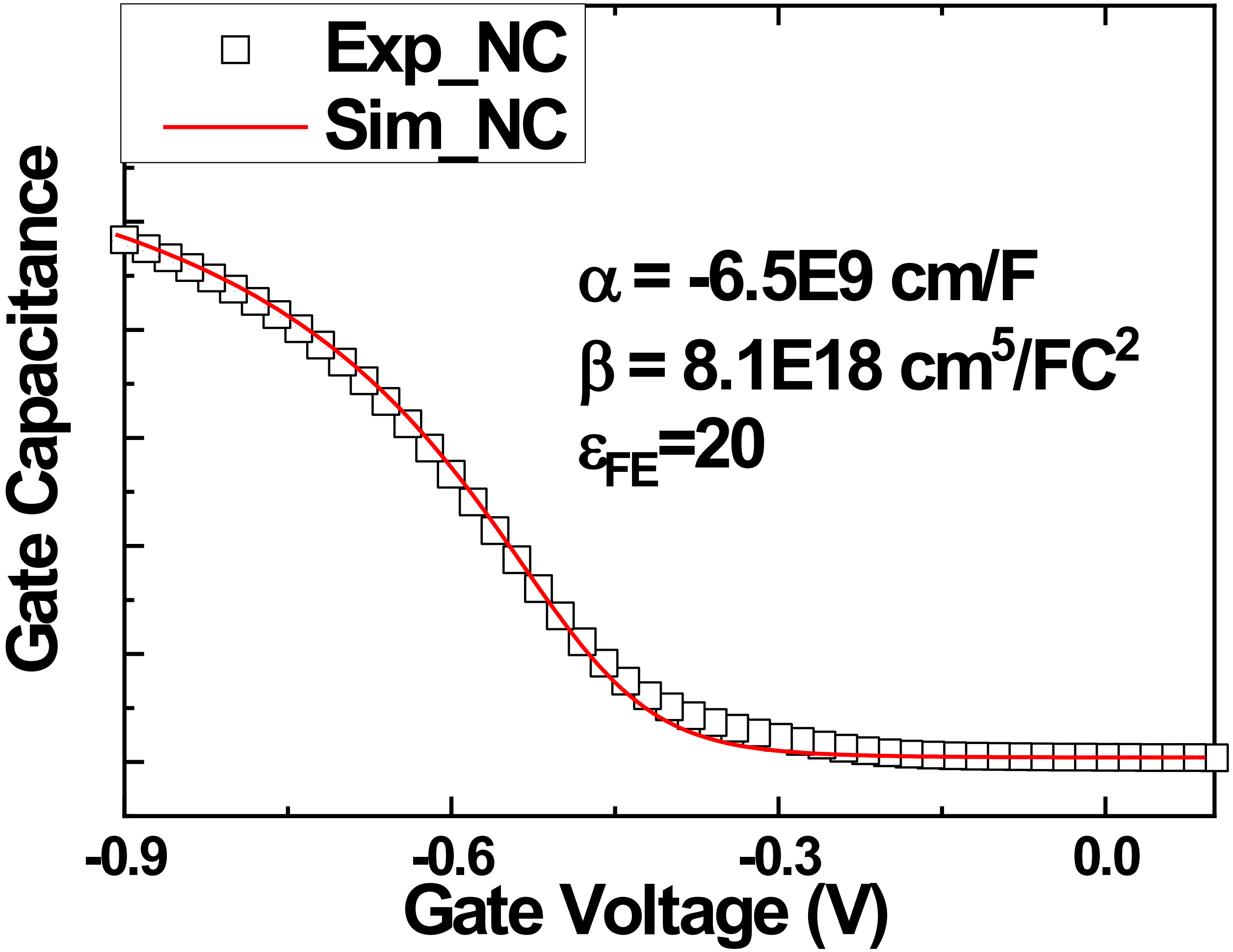




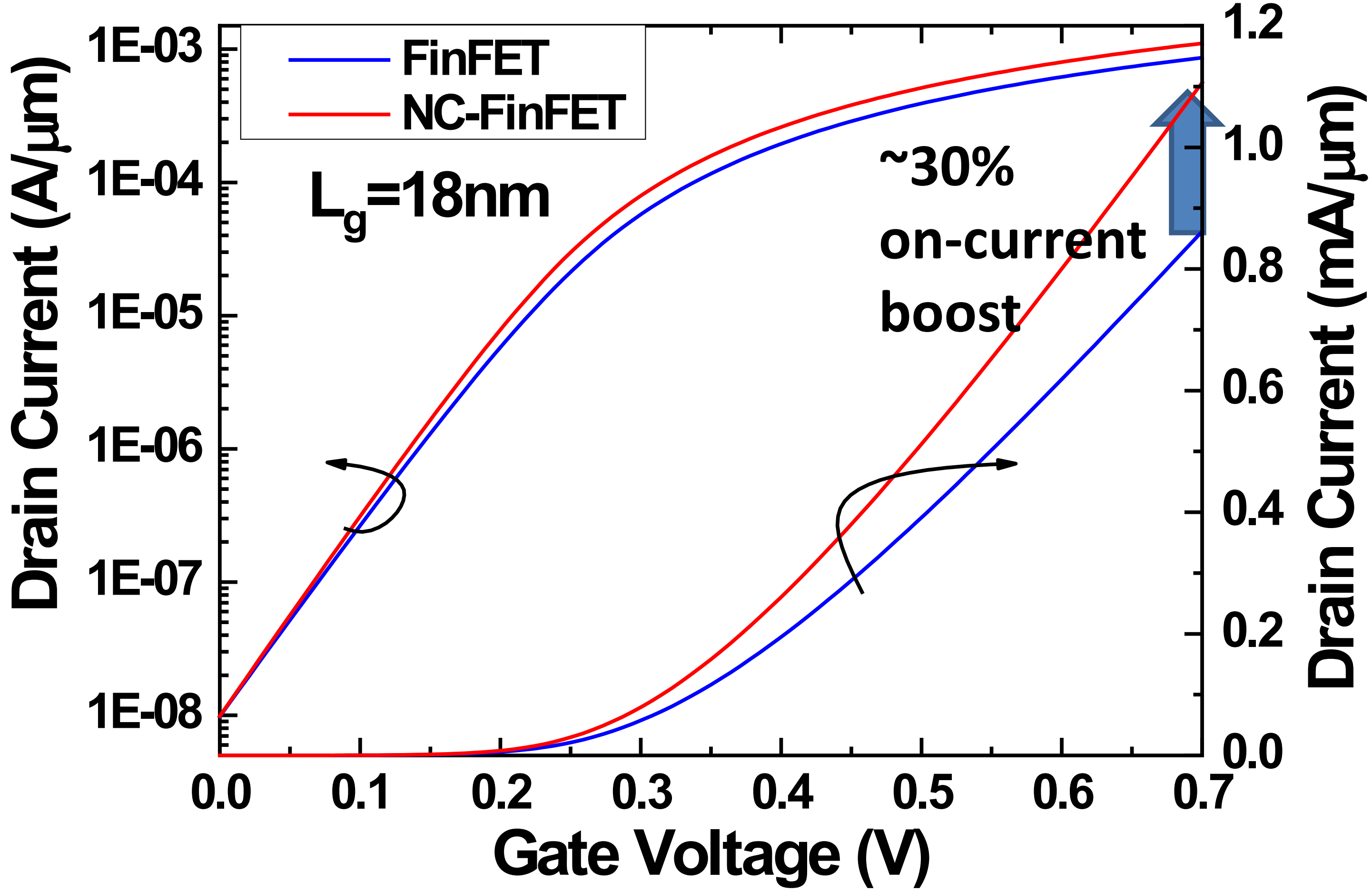
Step 3:
NC parameters extraction

HZO Experiment C-V [2]

[2]Sayeef's Group



Lg 18nm FinFET & NC-FinFET



At Lg=18nm, NC provide ~30% on-current boost

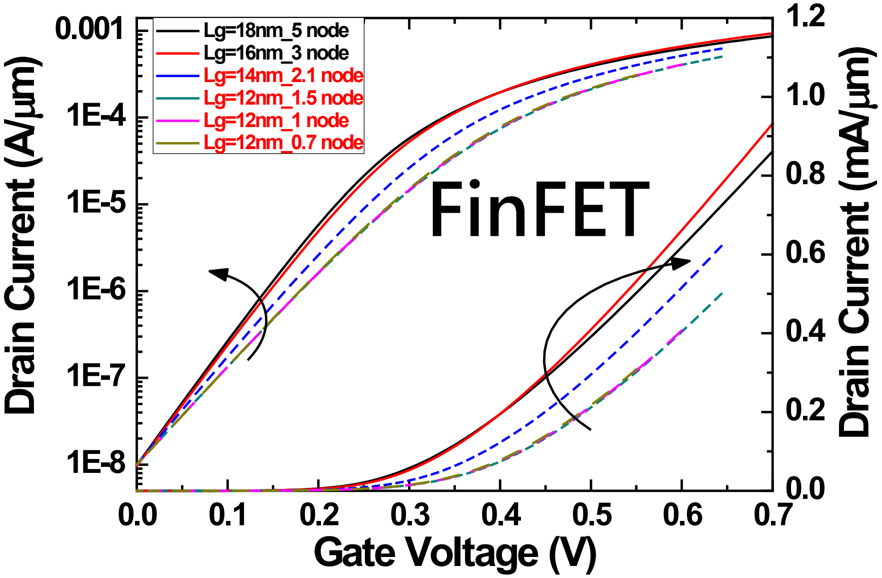
Step 4:
NC-FinFETs Scaling

Simulation Results of Scaling

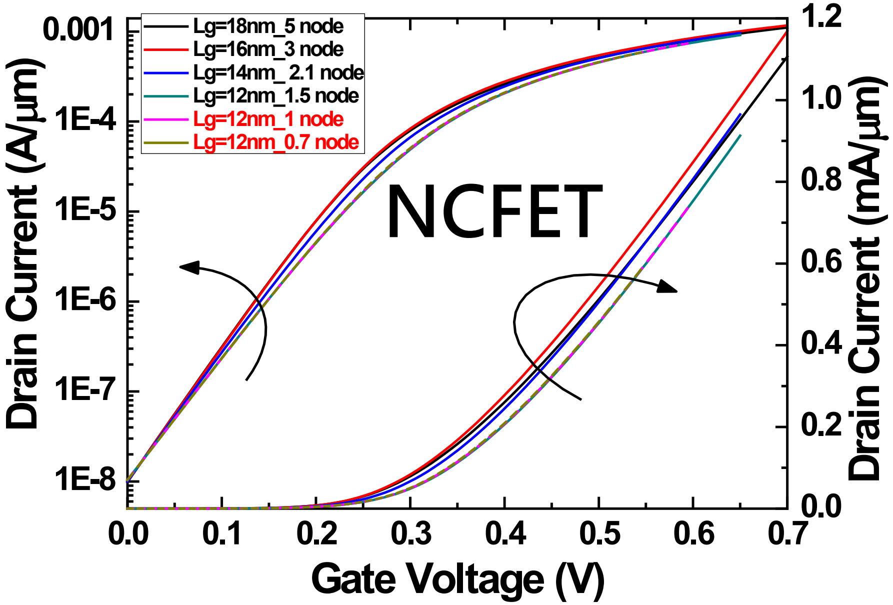
Theoretically, if we have uniform materials with that α and β, this is what we may expect to see.

<table>
<tr><th>1</th><th>“2018 IRDS” Node</th><th>“5”</th><th>“3”</th><th>“2.1”</th><th>“1.5”</th><th>“1.0 eq”</th><th>“0.7 eq”</th></tr>
<tr><td>2</td><td>Year of Production</td><td>2020</td><td>2022</td><td>2025</td><td>2028</td><td>2031</td><td>2034</td></tr>
<tr><td>3</td><td>Physical Gate Length (nm)</td><td>18</td><td>16</td><td>14</td><td colspan="3">12</td></tr>
<tr><td>4</td><td>Fin Width (nm)</td><td>7</td><td colspan="5">6</td></tr>
<tr><td>5</td><td>IRDS Target VDD (V)</td><td colspan="2">0.70</td><td colspan="2">0.65</td><td>0.60</td><td>0.55</td></tr>
<tr><td>6</td><td>Ion Target (mA/µm)</td><td>0.85</td><td>0.91</td><td>0.82</td><td>0.92</td><td>0.83</td><td>0.76</td></tr>
<tr><td>7</td><td>Ion of FinFET(mA/µm)</td><td>0.86</td><td>0.93</td><td>0.64</td><td>0.51</td><td>0.41</td><td>0.31</td></tr>
<tr><td>8</td><td>Ion of NC-FinFET(mA/µm)</td><td>1.11</td><td>1.17</td><td>0.97</td><td>0.92</td><td>0.75</td><td>0.60</td></tr>
</table>

Id-Vg

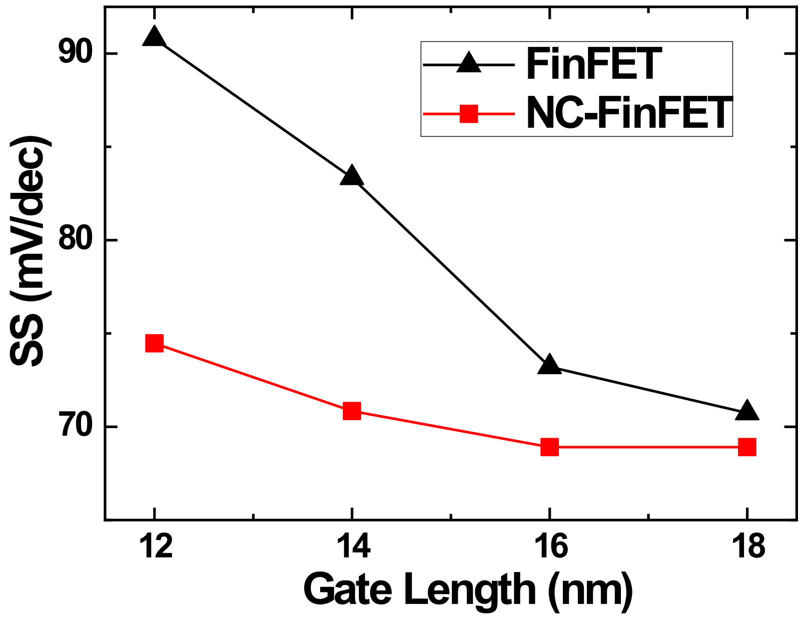


Lg=18nm_5 node
Lg=16nm_3 node
Lg=14nm_2.1 node
Lg=12nm_1.5 node
Lg=12nm_1 node
Lg=12nm_0.7 node
FinFET
Drain Current (A/μm)
Drain Current (mA/μm)
Gate Voltage (V)



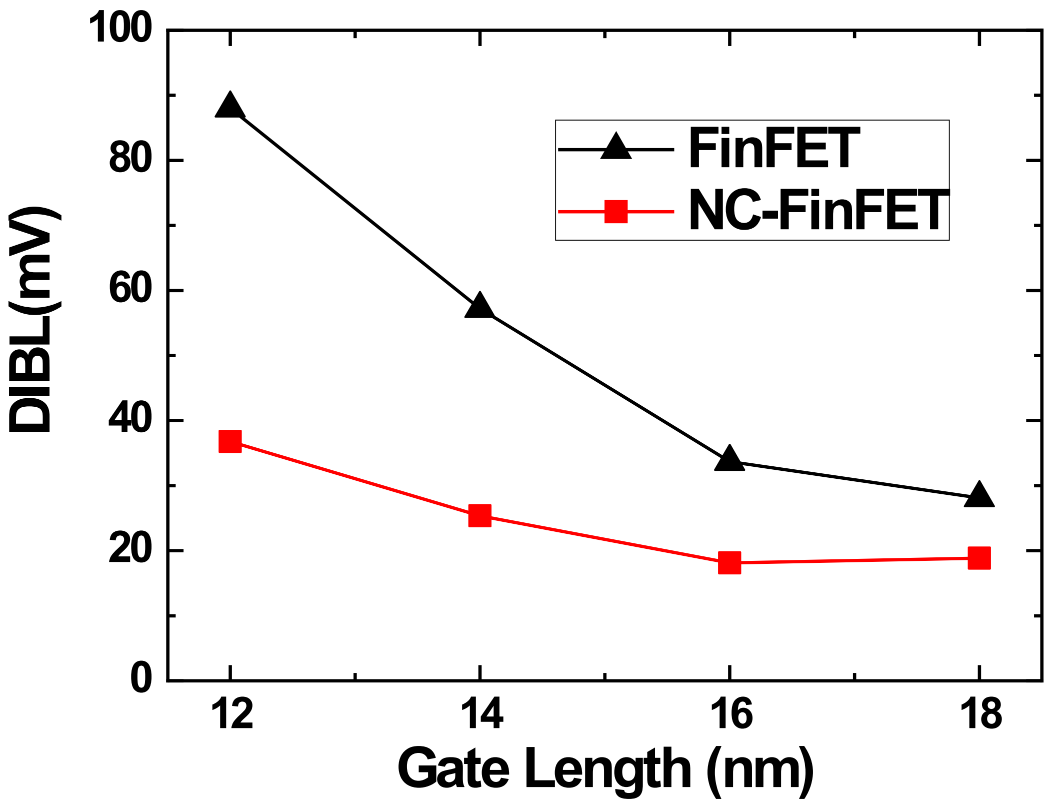
Lg=18nm_5 node
Lg=16nm_3 node
Lg=14nm_ 2.1 node
Lg=12nm_1.5 node
Lg=12nm_1 node
Lg=12nm_0.7 node
NCFET
Drain Current (A/μm)
Drain Current (mA/μm)
Gate Voltage (V)

Subthreshold Slope (SS)



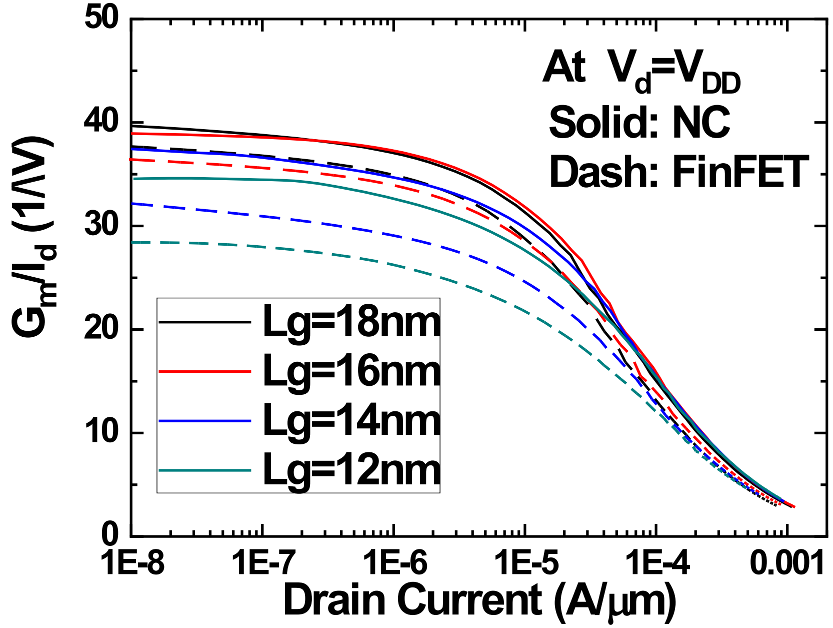
1. Sub 60mV/dec is not required
2. Capacitance matching makes NC benefits more in strong inversion
3. NC benefit more at smaller Lg
4. NC relieves SS degradation caused by Lg scaling

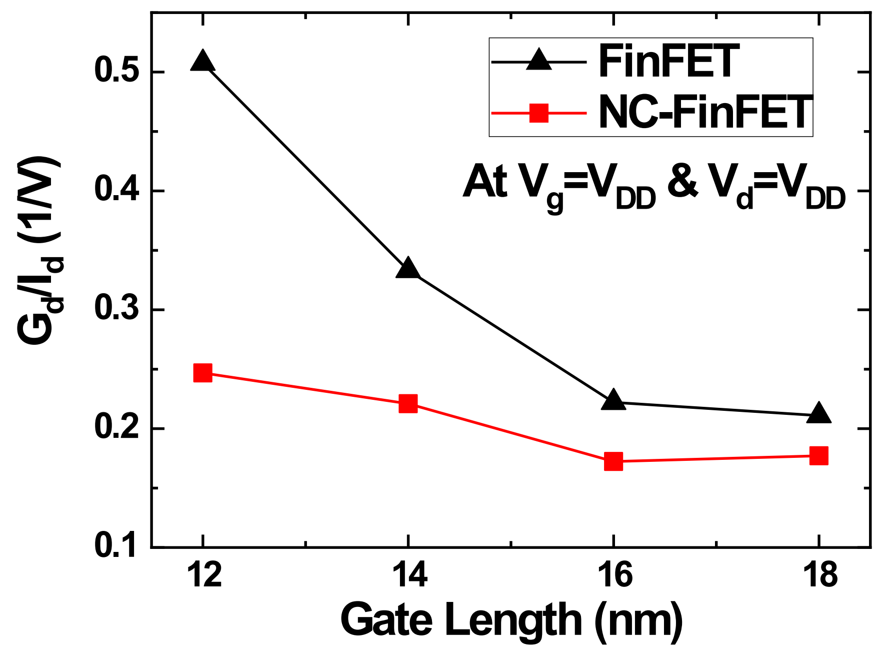
Drain Induced Barrier Lowering (DIBL)



DIBL is improved by NC

G_m/I_d & G_d/I_d for analog performance





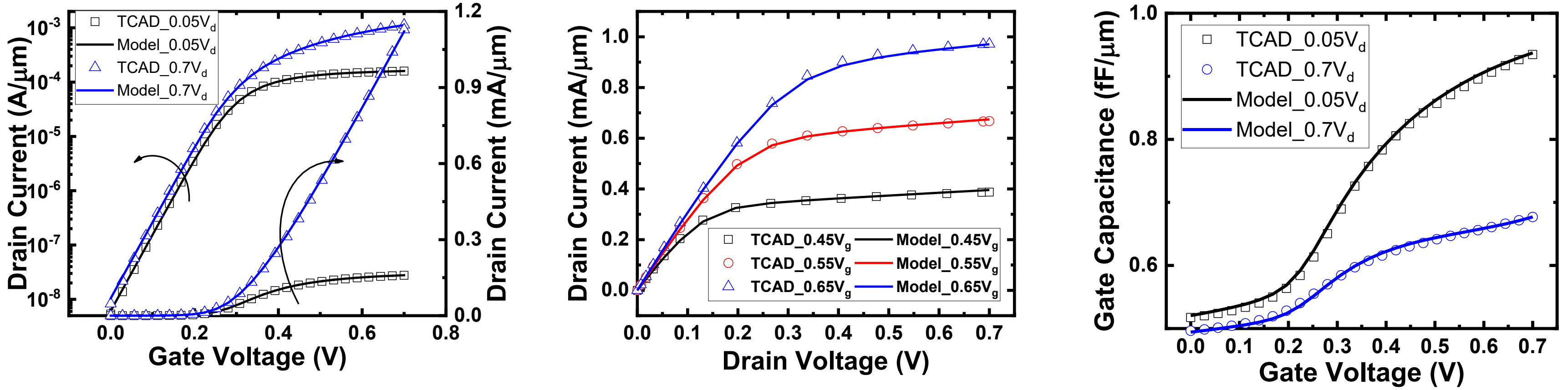
NC-FinFETs have higher G_m & lower G_d

NC achieves lower V_{DD}

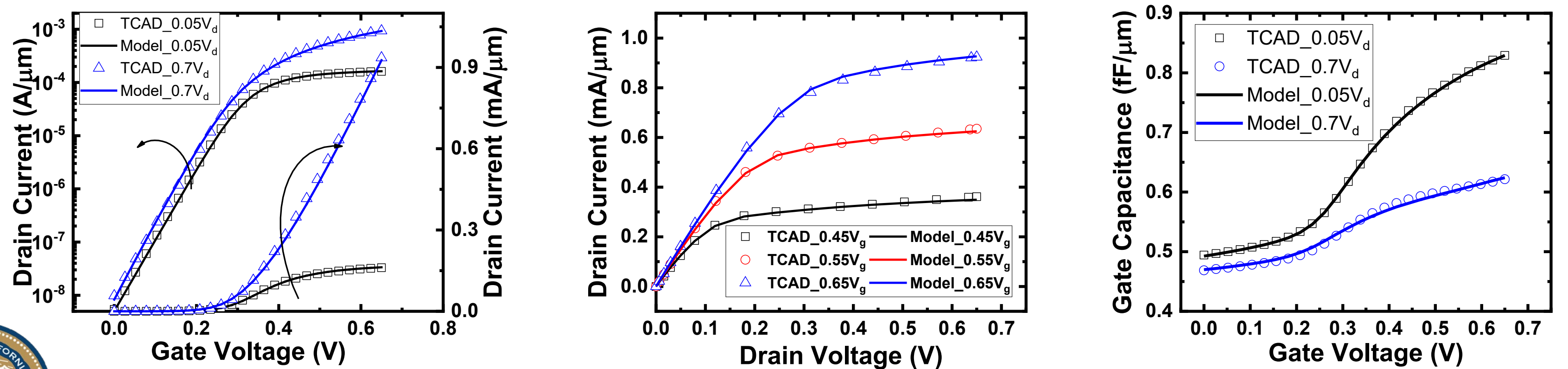
“2018 IRDS” Node	**“5”**	**“3”**	**“2.1”**	**“1.5”**	**“1.0 eq”**	**“0.7 eq”**
Year of Production	2020	2022	2025	2028	2031	2034
IRDS Target VDD (V)	0.70		0.65		0.60	0.55
FinFET V_{DD} needed to meet IRDS Target Ion	0.70	0.69	X	X	X	X
NC –FinFET V_{DD} needed to meet IRDS Target Ion	0.62	0.62	0.60	0.65	X	X

Compact Model Fitting, 16nm & 14nm

Lg=16nm



Lg=14nm



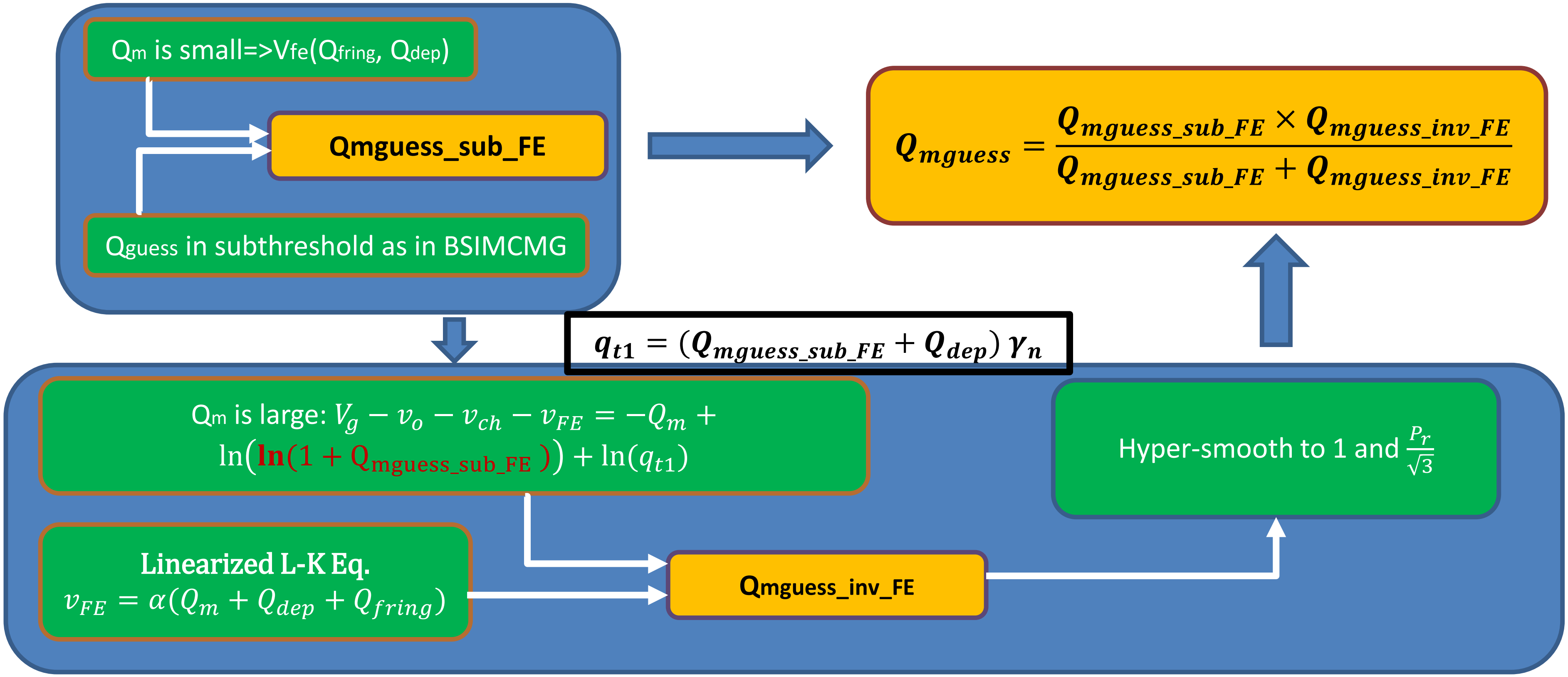
Conclusion

- FinFETs and nano-sheet FETs scaling may be extended by using NC.

Part II
NCFET Compact Model Enhancement

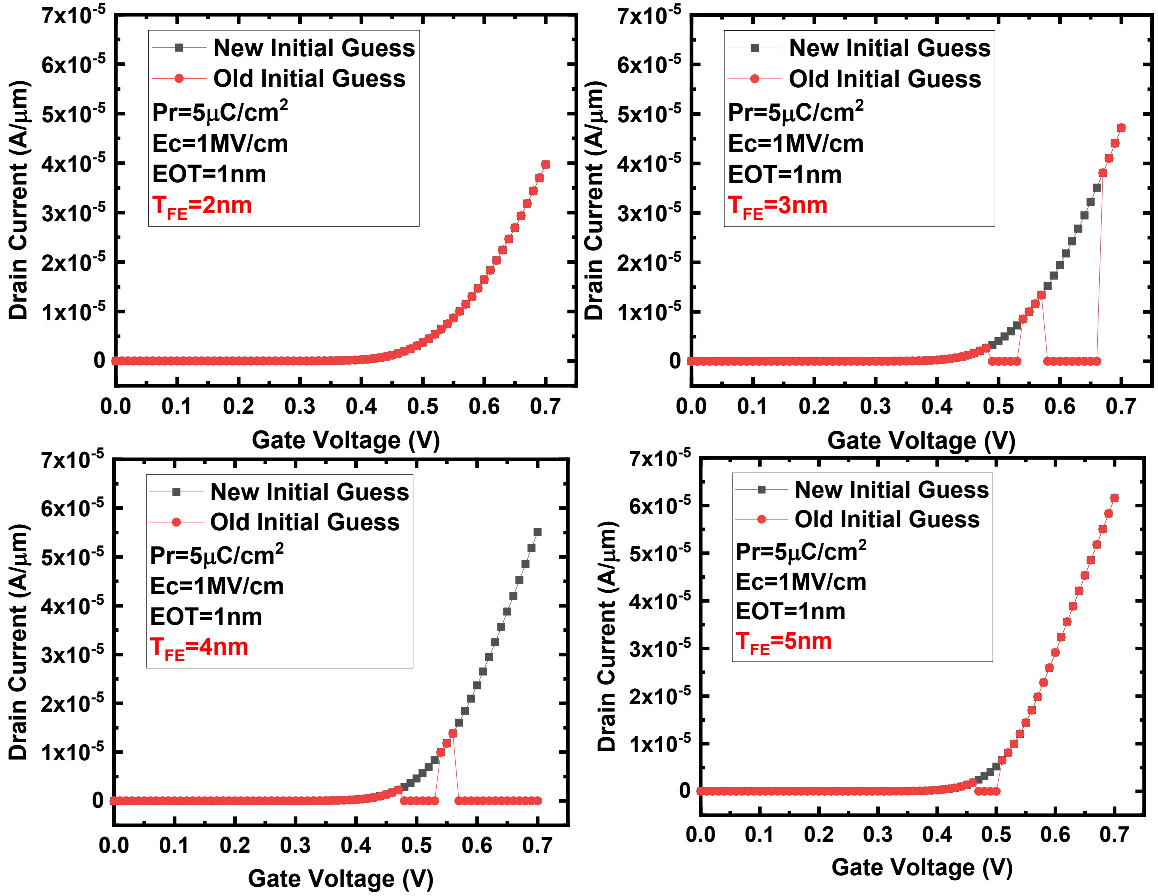
Improve the Convergence with better Initial Guess

Improve the convergence of NCFET Model



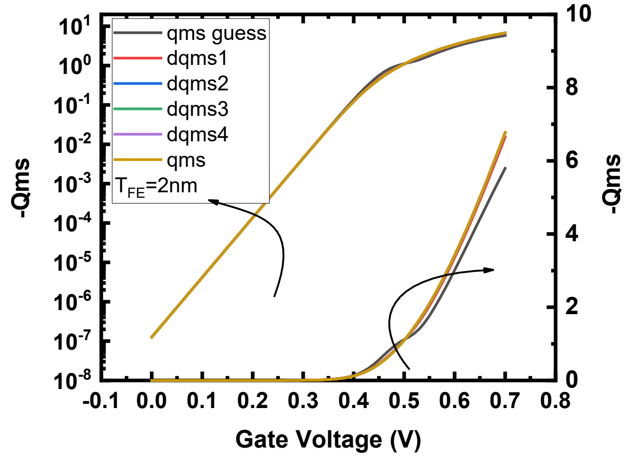
Convergence is improved by better initial guess in the inversion region.

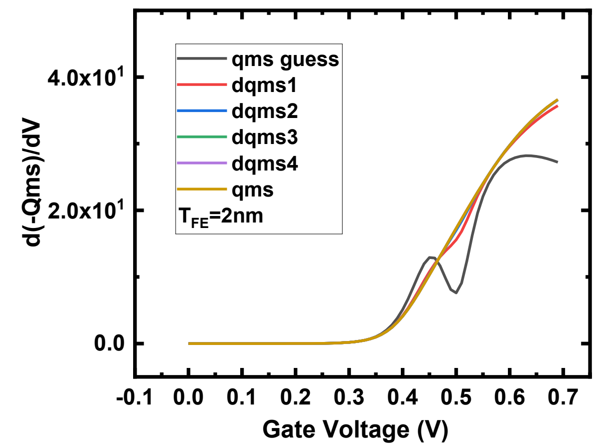
Improve the convergence of NCFET Model



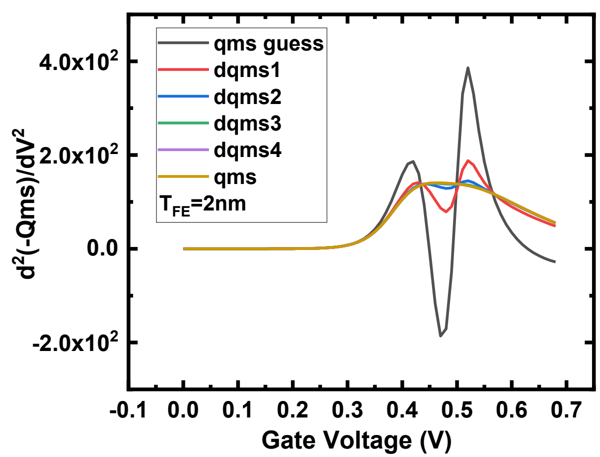
Q_{ms} per Iteration at T_{FE}=2nm

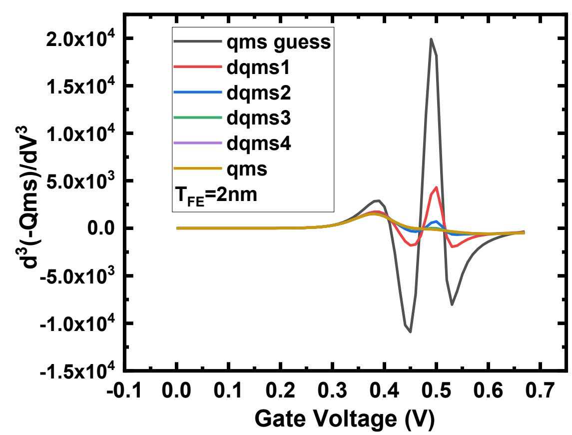
```
.model nmos1 bsimncfetbdmc
+ alpha1_P=-2.6e+9
+ alpha11_P=5.2e11
+ t_FE = 2e-9
+ NBODY = 1e22
+ EPSRFE = 0
```





Converge in 3 iterations

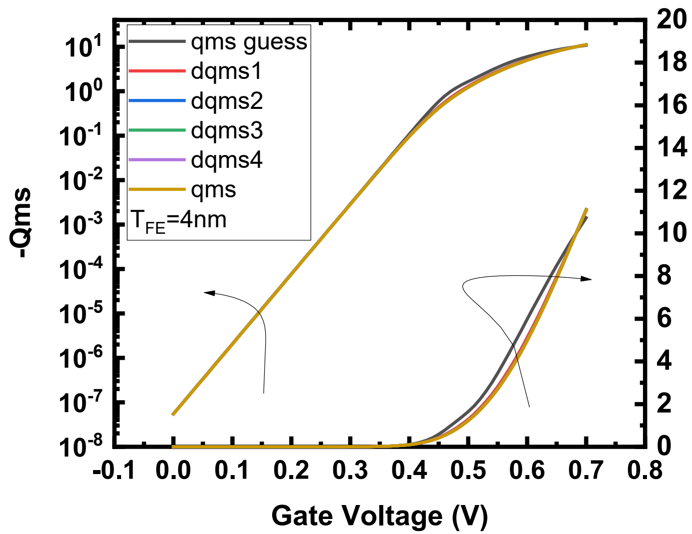


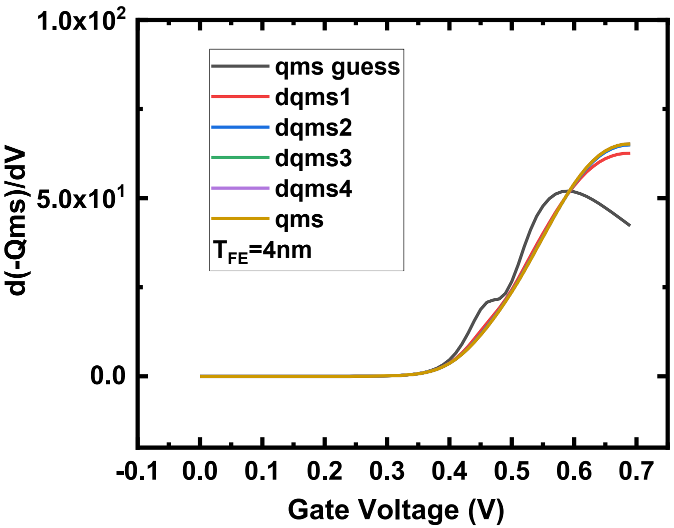


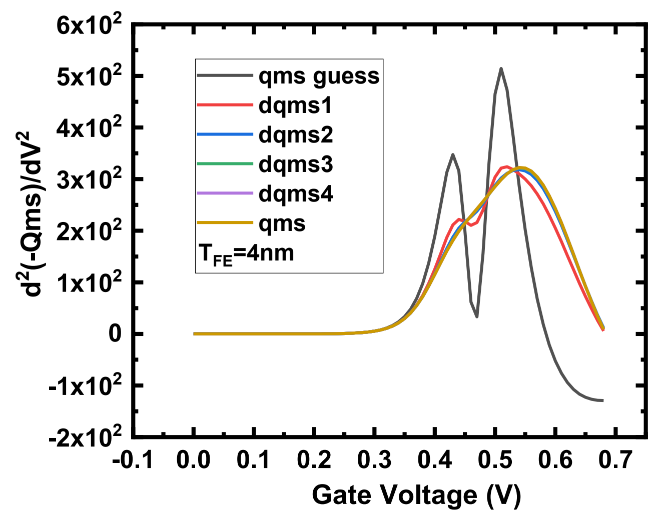
Q_{ms} per Iteration at T_{FE}=4nm

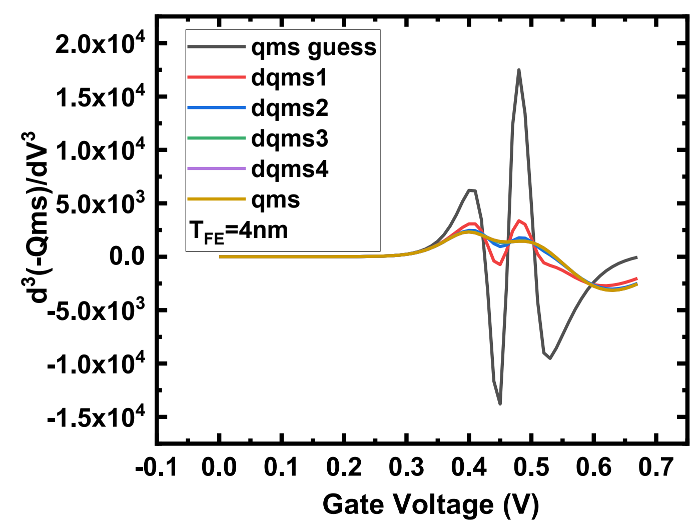
```
.model nmos1 bsimncfetbdmc
+ alpha1_P=-2.6e+9
+ alpha11_P=5.2e11
+ t_FE = 5e-9
+ NBODY = 1e22
+ EPSRFE = 0
```

Converge in 3 iterations









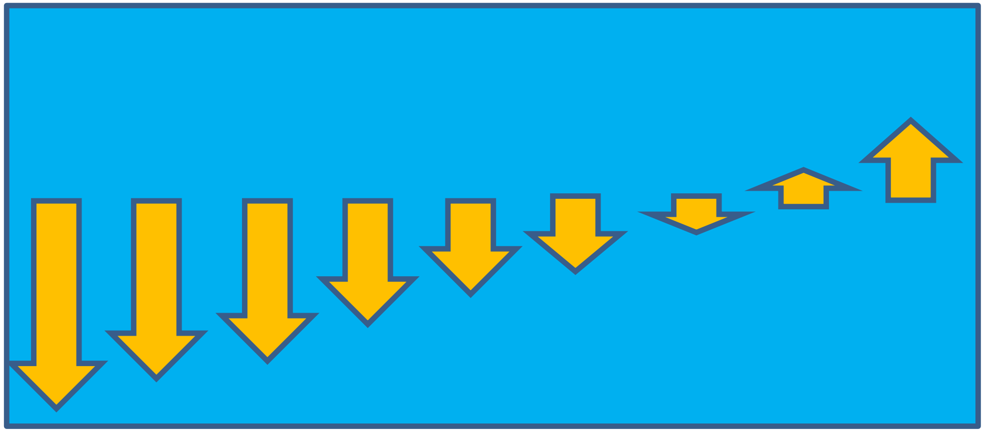
G TERM
(DOMAIN ENERGY COEFFICIENT)

Motivation

$$E = 2\alpha P + 4\beta P^3 + 6\gamma P^5 - 2g\nabla^2 P + \rho \frac{dP}{dt}$$

- **Negative DIBL** and **negative drain conductance** that measurement data show [3] cannot be fitted without g term.
- G term was not included in current model (NCFETBDMC1)

[3] H. Zhou et. al., VLSI, 2018



NCFETs Compact Model

Qms and qmd

Unified charge Eq. $V_g - v_o - v_{ch} - v_{FE} = -q_m + ln(q_m) + ln(q_t)$

Landau-Khalatnikov Eq.

$v_{FE} = tFE[\alpha(q_m + q_{dep} + q_{fring}) + \beta(q_m + q_{dep} + q_{fring})^3 + \cdots]$

Current Calculation

Gauss-Legendre quadrature:

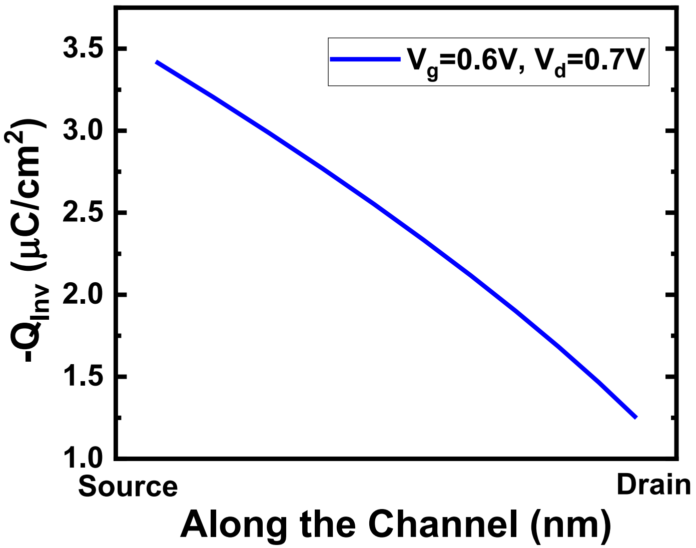
$$i_{DS} = \int_0^{V_{DS}} q_m dv_{ch} \approx \sum_{i=1}^{n} q_m(v_{ch,i})w_i$$

What is $\nabla^2 P$?

$$E = 2\alpha P + 4\beta P^3 + 6\gamma P^5 - 2g\nabla^2 P + \rho\frac{dP}{dt}$$

1. Consider 1-D: $\nabla^2 P = \frac{d^2P}{dx^2}$
2. $P \approx Q_g = Q_{inv} + Q_{dep} + Q_{fring}$
3. $\frac{d^2P}{dx^2} \approx \frac{d^2(Q_{inv}+Q_{fring})}{dx^2}$
4. Use Q_{inv} & Q_{fring} at g=0 in (3)

Evaluate $\frac{d^2 Q_{Inv}}{dx^2}$



$$q_{\mathrm{Inv}} = -(B - A\xi)^{\frac{1}{n}}$$

Constants B and A can be evaluated using B.Cs

1. $At\ \xi = 0, q_{Inv} = q_{is}$
2. $At\ \xi = 1, q_{Inv} = q_{idsat}$

$$\Rightarrow B = (-q_{is})^n$$

$$\Rightarrow A = (-q_{is})^n - (-q_{idsat})^n$$

$$\frac{d^2 q_{Inv}}{d\xi^2} = \frac{A^2(n-1)}{n^2}(B - Ax)^{\frac{1-2n}{n}}$$

Evaluate $\frac{d^2 Q_{Inv}}{dx^2}$

$$\frac{d^2 q_{Inv}}{d\xi^2} = \frac{A^2(n-1)}{n^2}(B - Ax)^{\frac{1-2n}{n}} \qquad \Rightarrow B = (-q_{Invs})^n$$

$$\Rightarrow A = (-q_{Invs})^n - (-q_{Invd})^n$$

At source side $\frac{d^2 q_{Invs}}{d\xi^2} \approx 0$, thus only consider Q_{Fring} in NCFET charge calculations.

At drain side $\frac{d^2 q_{Invd}}{d\xi^2} \approx \frac{(n-1)[(-q_{Invs})^n - (-q_{Invd})^n]^2}{n^2}(-q_{Invd})^{1-2n}$

Since $-q_{Invs}$ is known, $\frac{d^2 q_{Invd}}{dx^2}$ can be included in the Newton's method calculation

Evaluate $\frac{d^2 Q_{fring}}{dx^2}$

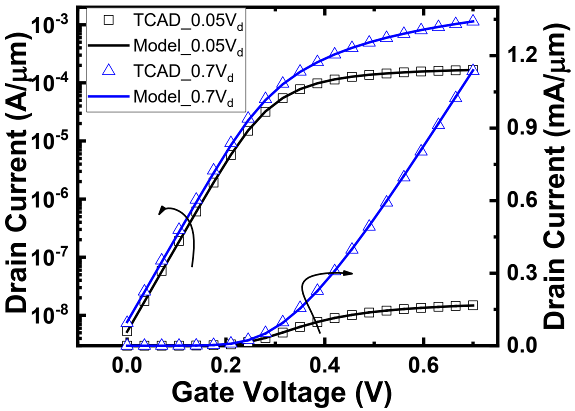
$$Q_{Fringing} \equiv -C_{IFFE}\,\{(V_{bi} - V_{SL})\frac{\sinh\left[\frac{L_g - x}{\lambda}\right]}{\sinh\left[\frac{L_g}{\lambda}\right]} + (V_{bi} + V_{DS} - V_{SL})\frac{\sinh\left[\frac{x}{\lambda}\right]}{\sinh\left[\frac{L_g}{\lambda}\right]}\}$$

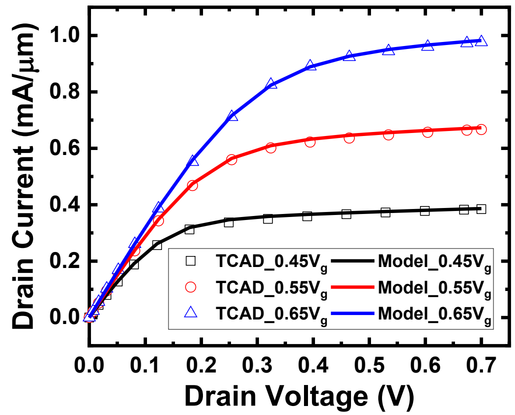
$$\frac{d^2 Q_{Fringing}}{dx^2} \equiv -\frac{C_{IFFE}}{\lambda^2}\{(V_{bi} - V_{SL})\frac{\sinh\left[\frac{L_g - x}{\lambda}\right]}{\sinh\left[\frac{L_g}{\lambda}\right]} + (V_{bi} + V_{DS} - V_{SL})\frac{\sinh\left[\frac{x}{\lambda}\right]}{\sinh\left[\frac{L_g}{\lambda}\right]}\}$$

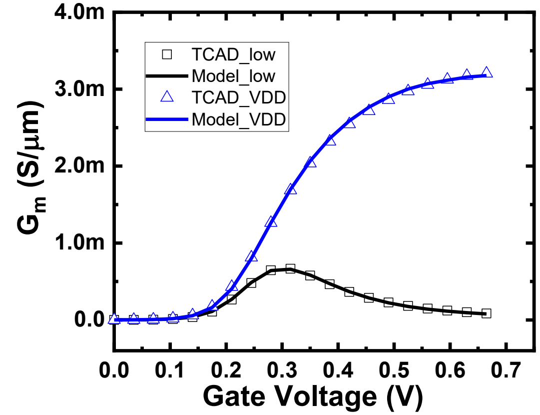
Final V_{FE} Equation

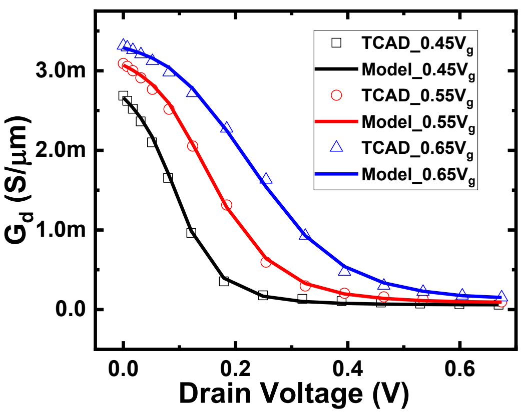
- $V_{FE} = t_{FE}\left[2\alpha P + 4\beta P^3 + 6\gamma P^5 - 2g\frac{d^2(Q_{inv}+Q_{fring})}{dx^2} + \rho\frac{dP}{dt}\right]$
- Where
  - $\frac{d^2Q_{Fring}}{dx^2} \equiv -\frac{Cox}{\lambda^2}\left\{(V_{bi} - V_{SL})\frac{\sinh\left[\frac{Lg-x}{\lambda}\right]}{\sinh\left[\frac{Lg}{\lambda}\right]} + (V_{bi} + V_{DS} - V_{SL})\frac{\sinh\left[\frac{x}{\lambda}\right]}{\sinh\left[\frac{Lg}{\lambda}\right]}\right\}$
    - Where x=l_{tob} at source; x= $L_g - l_{tob}$ at drain
  - $\frac{d^2q_{Invs}}{d\xi^2} \approx 0$ at source side
  - $\frac{d^2q_{Invd}}{d\xi^2} \approx \frac{(n-1)[(-q_{Invs})^n-(-q_{Invd})^n]^2}{n^2}(-q_{Invd})^{1-2n}$ at drain side

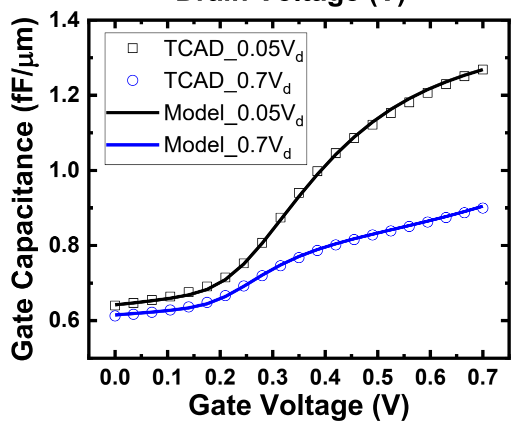
TCAD Fitting Results – Small g (5E-5 cm^3/F)



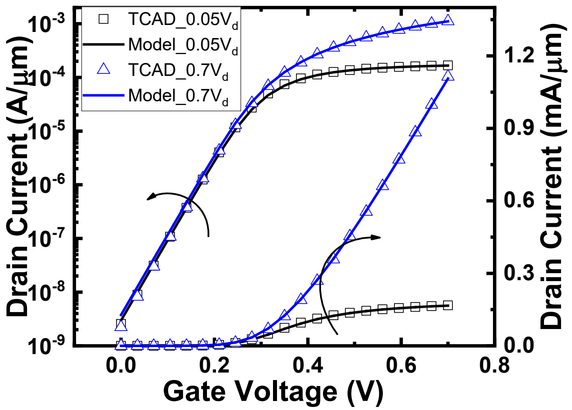


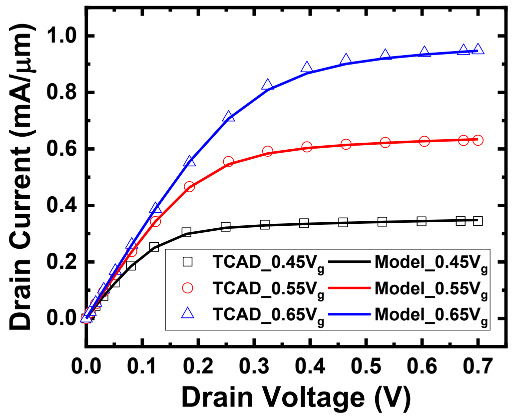


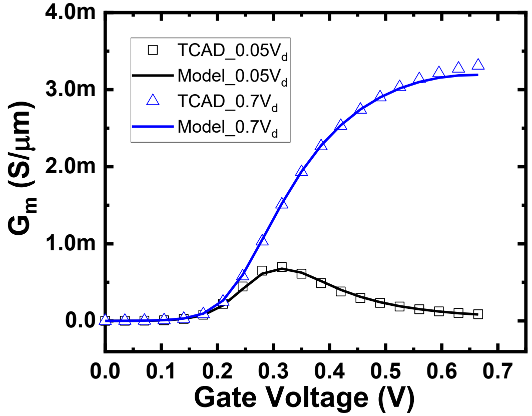


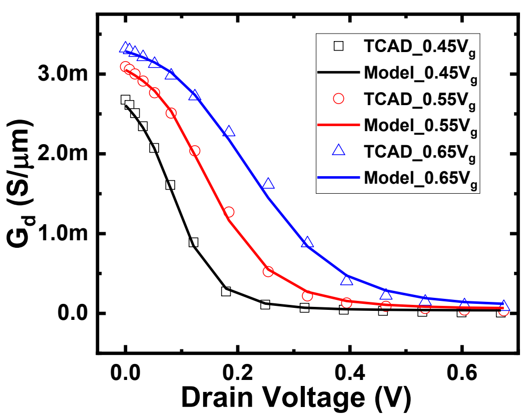


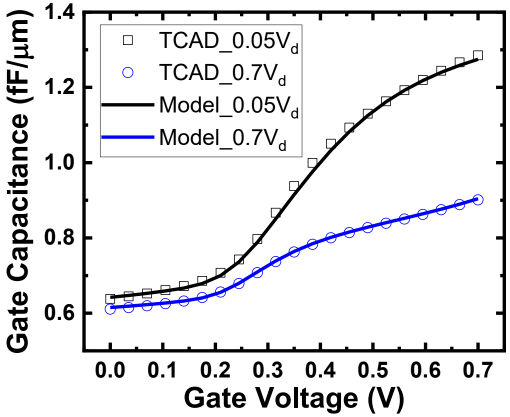
TCAD Fitting Results – Medium g (5E-4 cm^3/F)





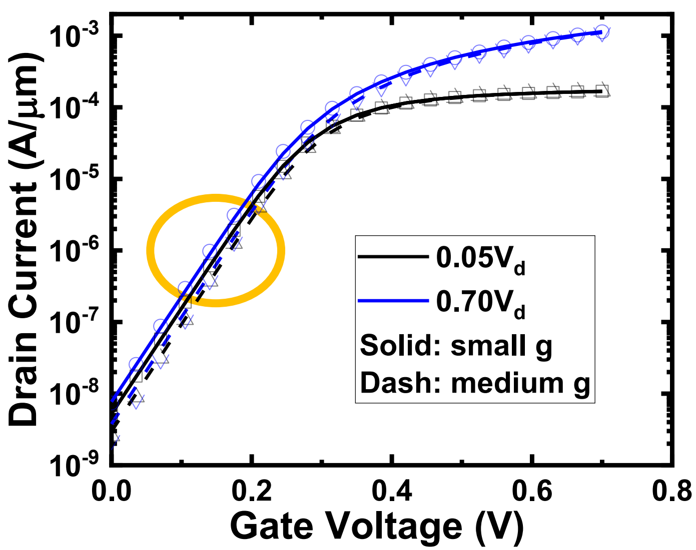


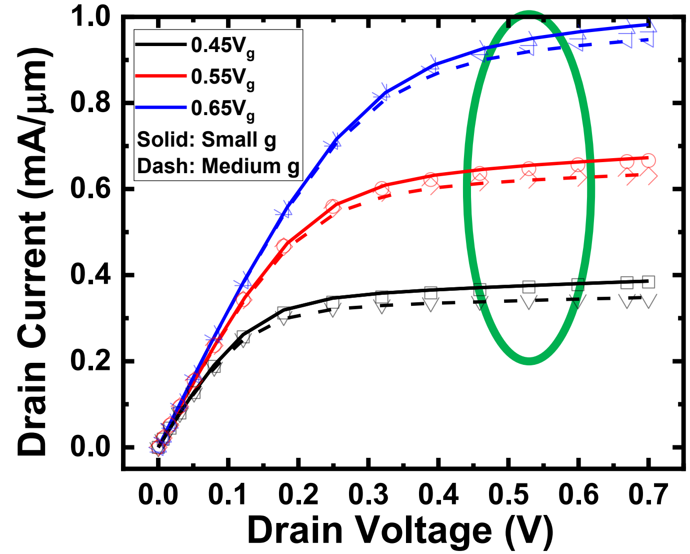




From Low g to Medium g, only parameter g is changed to get good fit.

Small g (5E-5 cm^3/F) vs Medium g (5E-4 cm^3/F)



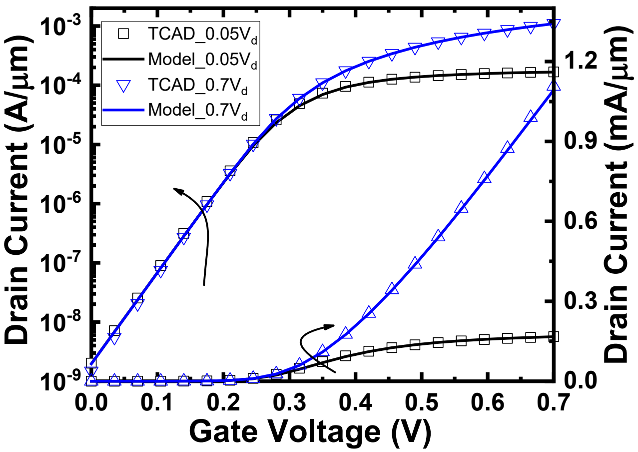


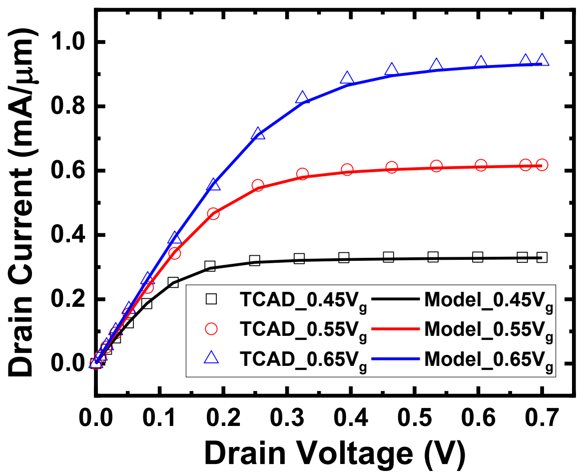
Less DIBL
Negative DIBL may appear if g is higher.

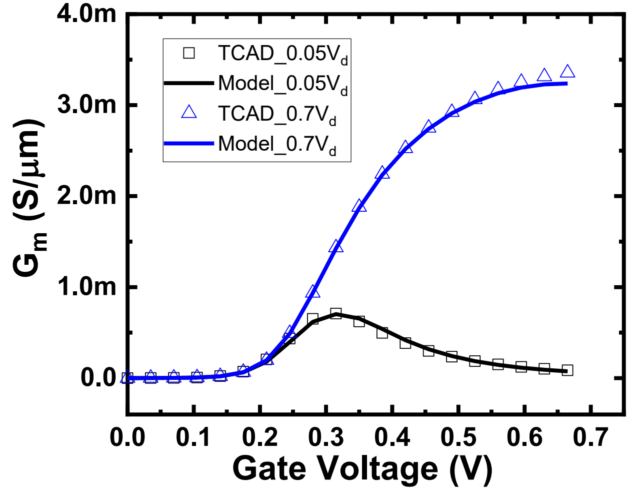
Less output conductance
Output conductance may be negative if g is higher.

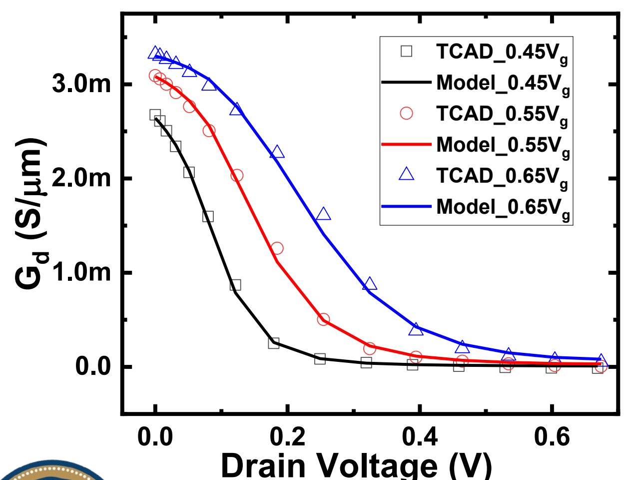
Less current especially in the off-state

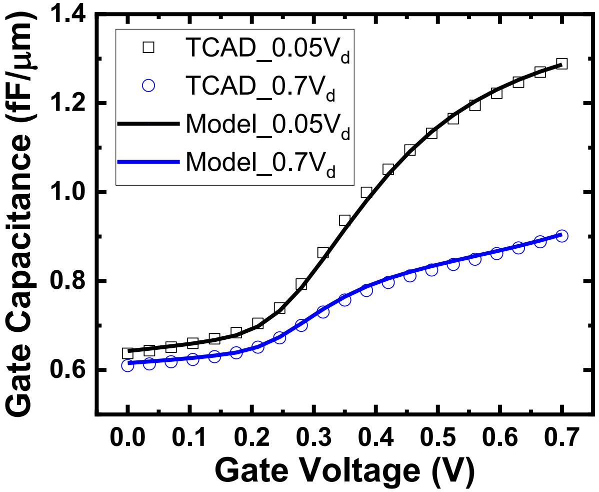
Predictive Model up to g=1E-3 (cm^3/F)
TCAD Fitting Results





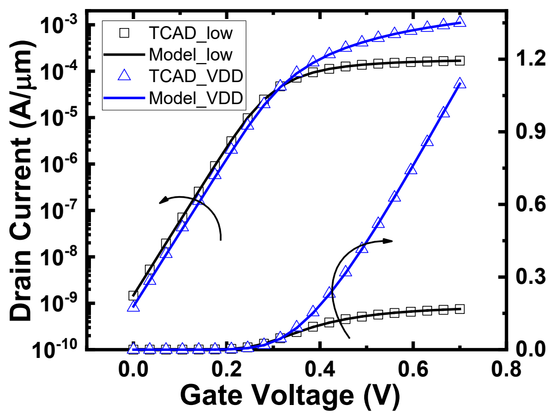


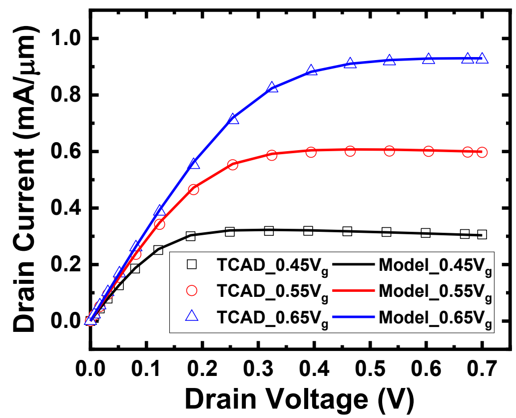


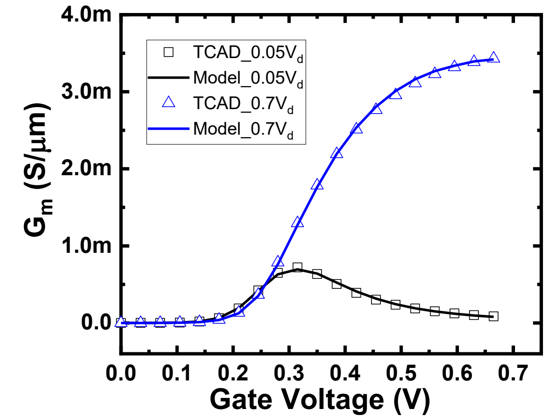


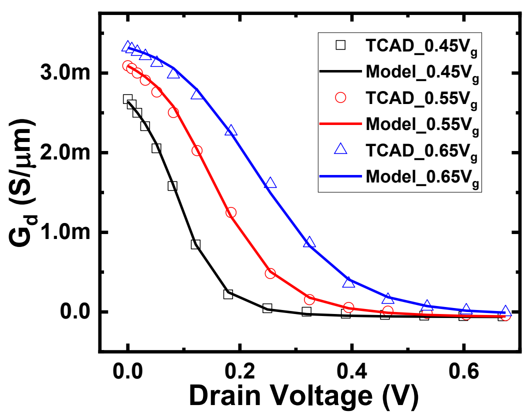
Only parameter, g, is changed and can fit TCAD data up to g=1E-3 (cm^3/F)

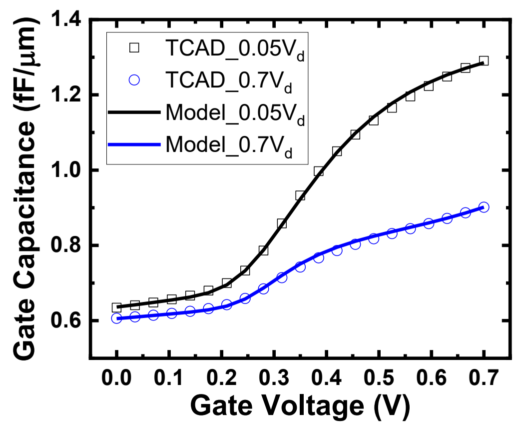
Used as fitting model:
TCAD Fitting Results – Large g (5E-3 cm^3/F)











Besides g, alfa, beta, mobility-related parameters, work-function, and fringing capacitance also need to be fine tuned....

Summery

- Convergence of the NCFET model is improved.
- G term has been implemented in BDMC NCFET Compact Model.
- Negative DIBL and Negative Drain Conductance are possibly to be achieve with the help of the g parameter.

g1	G parameter in Landau Equation
ng	Power of longitudinal variation of inversion charge
L_TOB	Source side distance to the top of the barrier

Thank you

Any Question?