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LINFET: A BSIM Class FET Model with Smooth Derivatives at V_{ds}=0

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Toy Model

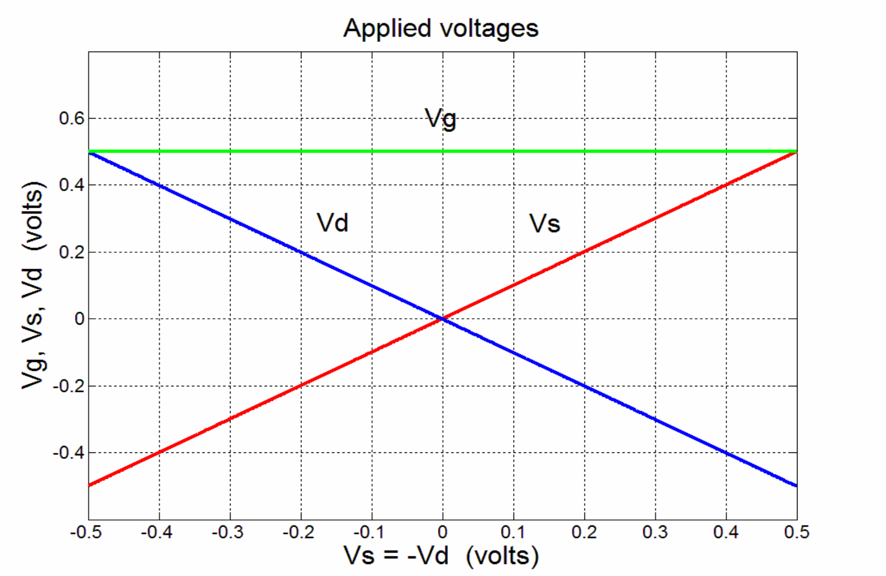
- **Original**
  - Variables: V_{gs}, V_{ds}
  - Parameters: V_t, μ

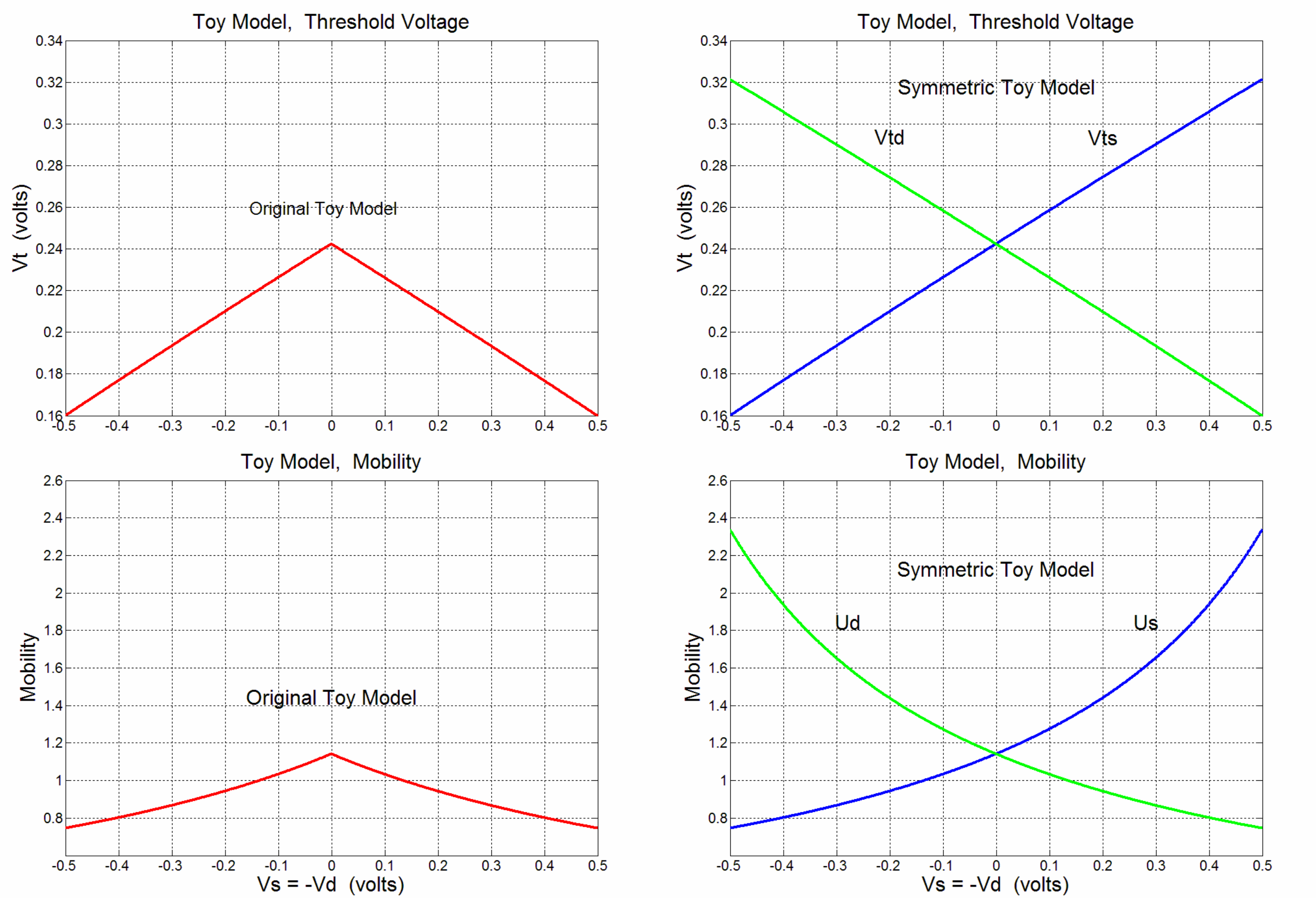
$$J_{ds} = \frac{2WC_{ox}\mu}{L}\left(V_{gst} - \frac{V_{ds}}{2}\right)V_{ds}$$

$$(V_{ds} \geq 0)$$

- **Symmetric**
  - Variables: V_{gs}, V_{gd}
  - Parameters: V_{ts}, V_{td}, μ_s, μ_d

$$J_{ds} = \frac{WC_{ox}}{L}\left(\mu_s V_{gst}^2 - \mu_d V_{gdt}^2\right)$$




Toy Model, Threshold Voltage
Vt (volts)
Original Toy Model
Toy Model, Threshold Voltage
Vt (volts)
Symmetric Toy Model
Vtd
Vts
Toy Model, Mobility
Mobility
Original Toy Model
Vs = -Vd (volts)
Toy Model, Mobility
Mobility
Symmetric Toy Model
Ud
Us
Vs = -Vd (volts)

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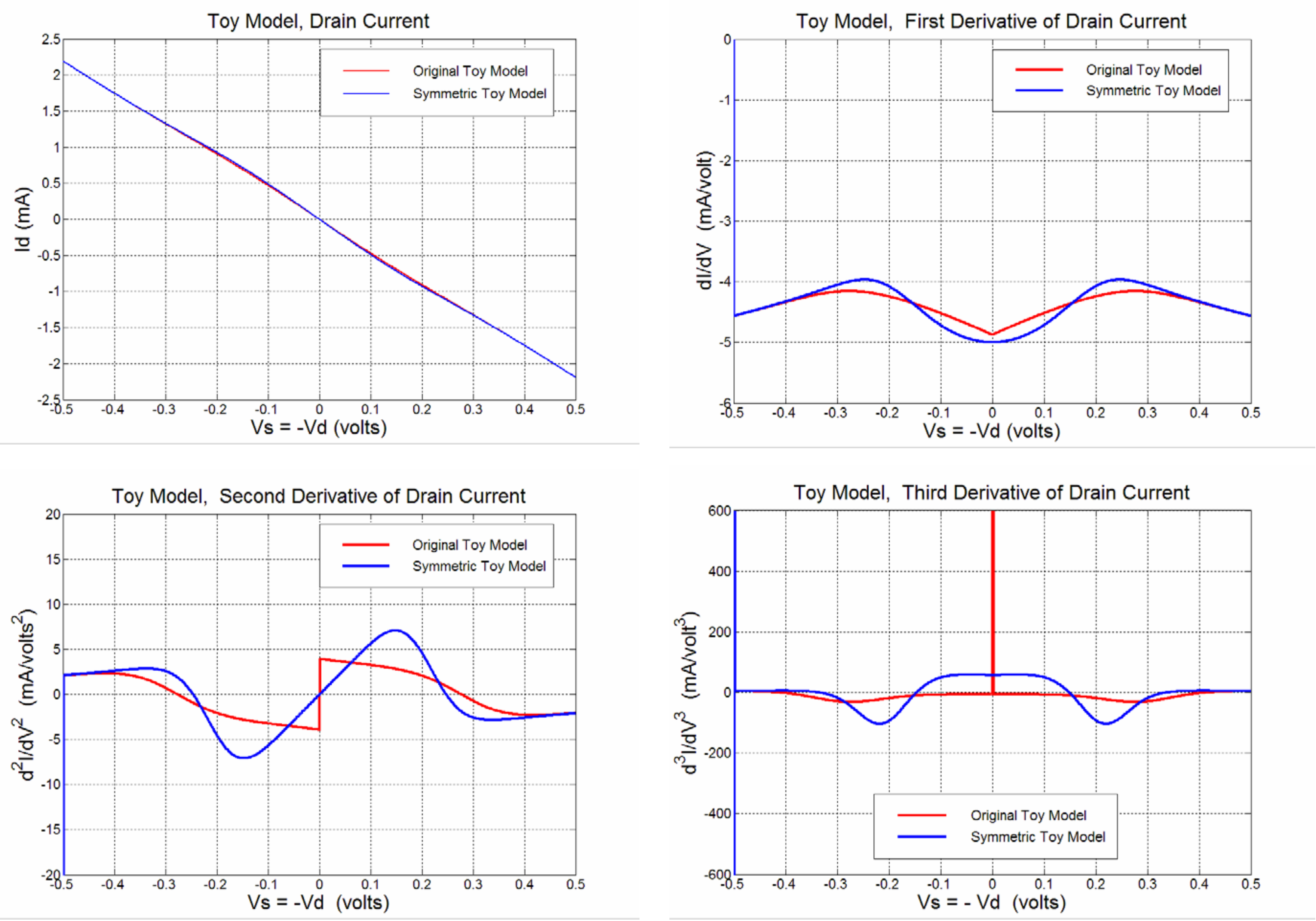


Introduction

- **The linearity of a compact transistor model at or near V_{ds}=0 is important for the design of RF circuits such as mixers and switches.**
- **Currently established compact FET models such as BSIM3/4, and others have traditionally had problems around this bias point.**
- **In this paper we show how discontinuities in the derivatives of the drain current and charges arise in the threshold based BSIM model, and a method of fixing them is suggested.**

Derivation of the intrinsic BSIM model

- **Channel charge**

$$q_g(y) = -q_c(y) - q_b(y) = \varepsilon_{si} E_{si} = \varepsilon_{ox} E_{ox}$$
$$= C_{ox}\left(\psi_g - \psi_c(y)\right) \approx C_{ox}\left(V_g - V_c(y) - V_{t0}\right)$$

- **Bulk charge linearized**

$$-q_b(y) = \sqrt{2q\varepsilon_{si} N_a \left(V_{bi} + V_c(y) - V_b\right)}$$
$$\approx \alpha C_{ox}\left[2V_{bi} + \left(V_c(y) - V_b\right) + \ldots\right]$$

$$\alpha = \frac{1}{C_{ox}}\sqrt{\frac{q\varepsilon_{si} N_a}{2V_{bi}}}$$

- **Integrate the drain to source current**

$$J_{ds} = -\mu_n q_c(y)\frac{\partial V_c}{\partial y} = \frac{1}{L}\int_0^L J_{ds}\,dy = \frac{\mu_n}{L}\int_{V_s}^{V_d} q_c(V_c)\,dV_c = \frac{C_{ox}\mu_n}{2(1+\alpha)}\left(V_{gst}^2 - V_{gdt}^2\right)$$

BSIM model substitutions

- **At this point the BSIM model changes variables from V_{gs} and V_{gd}, to V_{gs} and V_{ds}.**

$$V_{ds} = V_d - V_s$$

$$V_{gdt} = V_{gst} - (1+\alpha)V_{ds}$$

- **The result is**

$$J_{ds} = \frac{C_{ox}\mu_n}{L}\left[V_{gst} - \frac{(1+\alpha)V_{ds}}{2}\right]V_{ds}, \qquad V_{ds} \geq 0$$

- **This destroys the source/drain symmetry when a voltage dependence is added to quantities that have been considered to be constant up to now.**

BSIM modifications that destroy symmetry

- **Threshold voltage:**

$$V_{ts} = V_{t0} + \alpha\left(2V_{bi} - V_{bs}\right) \approx V_{t0} + \sqrt{2q\varepsilon_{si}N_a\left(V_{bi} - V_{bs}\right)} + \ \ldots$$

$$J_{ds} = \frac{C_{ox}\mu_n}{L}\Big[\max\left(V_{gs},\, V_{gd}\right) - V_{t0} - \sqrt{2q\varepsilon_{si}N_a\left(V_{bi} - \max\left(V_{bs},\, V_{bd}\right)\right)} - \frac{(1+\alpha)\left|V_{ds}\right|}{2}\Big]V_{dseff}$$

- **Mobility:** $\mu_n = \mu_n\left(V_{gst}, V_{bs}\right)$
- **Bulk charge factor:** $A_{bulk} = \left(1+\alpha\right) = A_{bulk}(V_{gst}, V_{bs})$
- **The $V_{ds} \approx V_{dseff}$ is not symmetric.**
- **Other**

Physical Picture for LINFET

- **BSIM first integrates the drain to source current, and then makes the parameters V_t, μ_n, and α voltage dependent.**

$$J_{ds} = \frac{\mu_n}{L} \int_{V_s}^{V_d} q_c\left(V_c\right) dV_c = \frac{C_{ox}\mu_n}{2\left(1+\alpha\right)} \left(V_{gst}^2 - V_{gdt}^2\right) = J_s - J_d$$

- **This suggests that we define two opposing currents, with voltge dependent parameters defined at the source and the drain.**

$$J_s = \frac{C_{ox}\mu_{ns}}{2\left(1+\alpha_s\right)} \left(V_g - V_s - V_{ts}\right)^2$$

$$J_d = \frac{C_{ox}\mu_{nd}}{2\left(1+\alpha_d\right)} \left(V_g - V_d - V_{td}\right)^2$$

LINFET approach

- **The current equation is factored.**
  - The $\boldsymbol{V_{gst}}$ and $\boldsymbol{V_{gdt}}$ dependence is retained.
  - Notice the fortuitous cancelation of the bulk charge factor **(1 + α).**

$$J_{ds} = \frac{C_{ox}\mu_n}{2(1+\alpha)L}\left(V_{gst}^2 - V_{gdt}^2\right) = \frac{C_{ox}\mu_n}{L}\left(\frac{V_{gst}+V_{gdt}}{2}\right)V_{ds}$$

- **We keep two threshold voltage expressions.**

$$V_{ts} = V_{t0} + \alpha\left(2V_{bi} - V_{bs}\right) \approx V_{t0} + \sqrt{2q\varepsilon_{si}N_a\left(V_{bi} - V_{bs}\right)} + \ ...$$

$$V_{td} = V_{t0} + \alpha\left(2V_{bi} - V_{bd}\right) \approx V_{t0} + \sqrt{2q\varepsilon_{si}N_a\left(V_{bi} - V_{bd}\right)} + \ ...$$

LINFET approach (continued)

- **The mobility can be handled in two ways.**

$$J_{ds} = \frac{C_{ox}}{L}\left(\frac{\mu_{ns}V_{gst} + \mu_{nd}V_{gdt}}{2}\right)V_{dseff}$$

$$\mu_{ns} = \mu_{ns}\left(V_{gst}, V_{bs}\right)$$

$$\mu_{nd} = \mu_{nd}\left(V_{gdt}, V_{bd}\right)$$

- **Or**

$$J_{ds} = \frac{C_{ox}}{L}\left(\mu_{neff}\left(\mu_{ns}, \mu_{nd}\right)\right)\left(\frac{V_{gst} + V_{gdt}}{2}\right)V_{dseff}$$

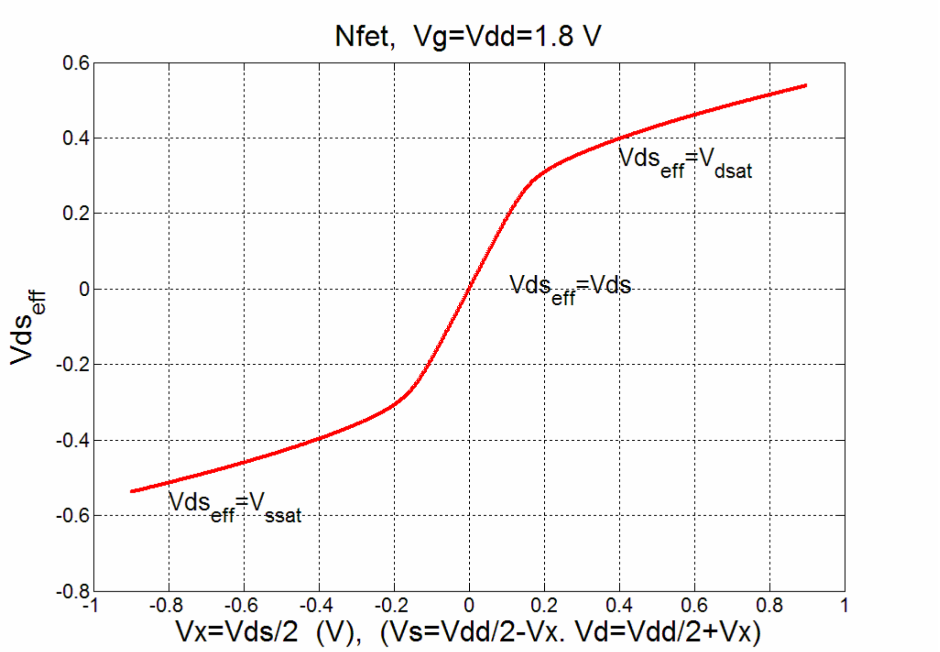
$$\frac{1}{\mu_{neff}} = \frac{1}{2}\left(\frac{1}{\mu_{ns}} + \frac{1}{\mu_{nd}}\right)$$

LINFET approach (continued)

- **The effective V_{dseff} factor can be written in a symmetric manor.**
  - We define two saturation voltages for the source and drain.
  - The δ term can be used as a fitting factor.

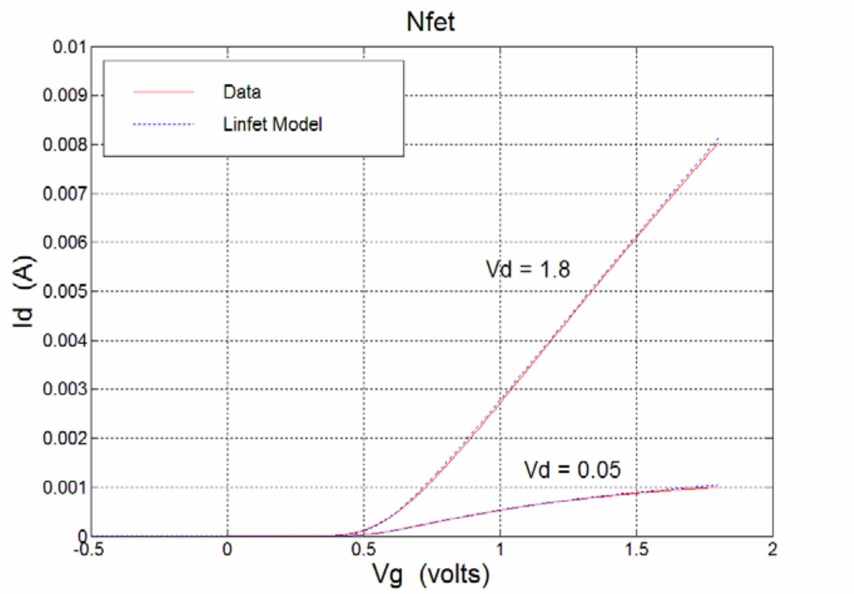
$$V_{dseff} = \frac{1}{2}\Big[V_{dsats} - V_{ssatd} - \sqrt{\left(V_{dsats} - V_{ds}\right)^2 + 4\delta\left(V_{dsats} + \delta\right)} + \sqrt{\left(V_{ssatd} + V_{ds}\right)^2 + 4\delta\left(V_{ssatd} + \delta\right)}\Big]$$

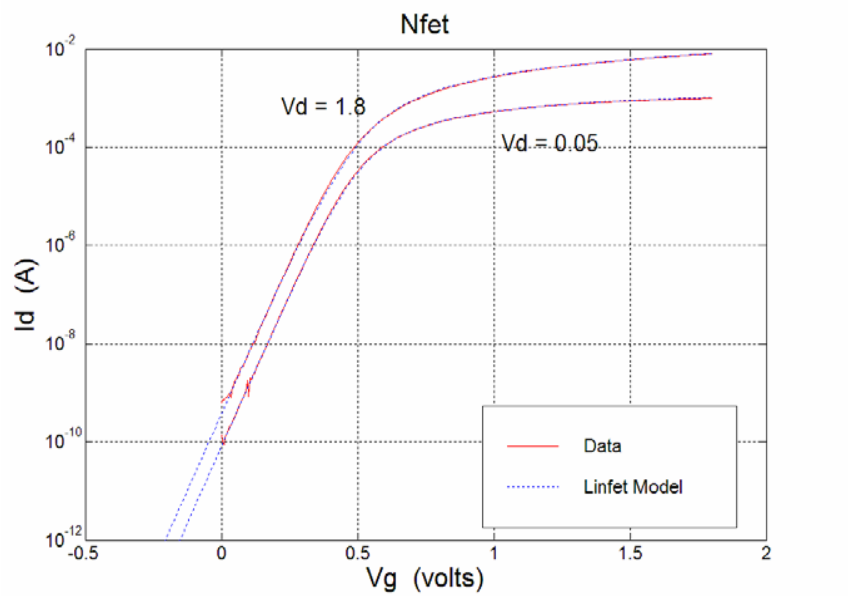
$$V_{dsats} = V_{dsat}\left(V_{gst}\right), \quad V_{ssatd} = V_{dsat}\left(V_{gdt}\right)$$

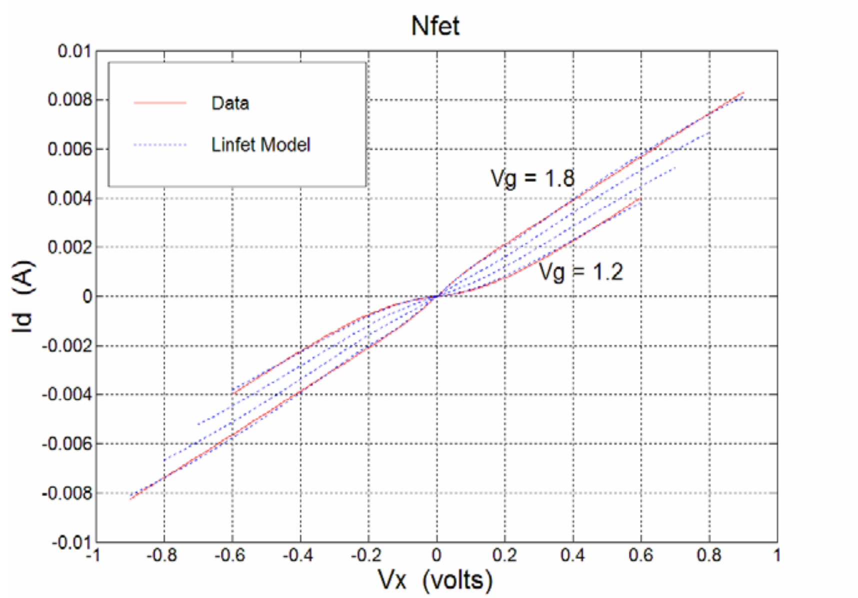


LINFET approach (continued)

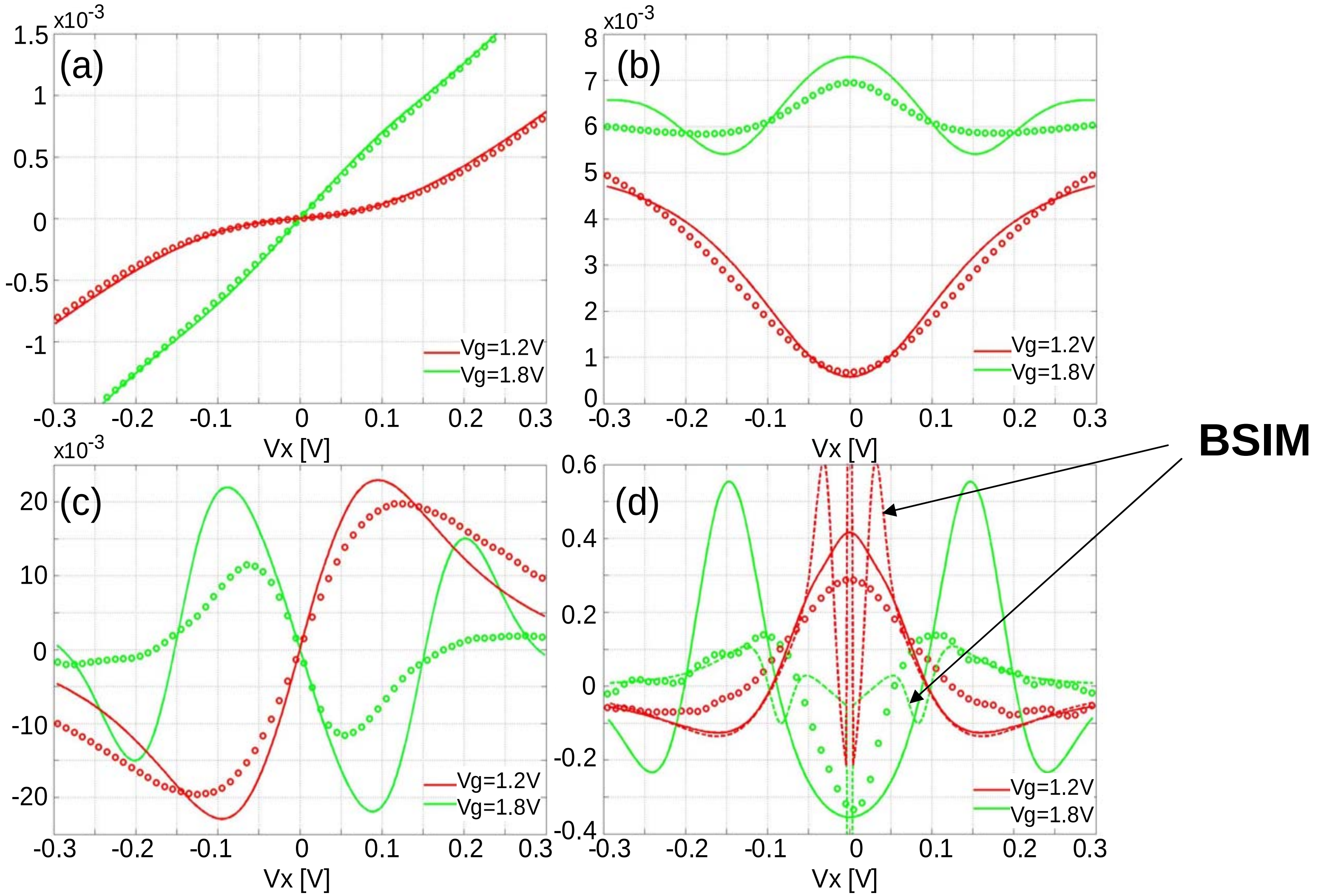
- **Voltage dependent BSIM parameters evaluated at both the drain and the source.**
  - V_{th} Threshold Voltage
  - μ_{eff} Effective mobility
  - V_{dsat} Saturation voltage
  - E_{sat} Electric field
  - V_A Early voltage
  - A_{bulk} Bulk charge factor


Nfet
Data
Linfet Model
Vd = 1.8
Vd = 0.05
Id (A)
Vg (volts)

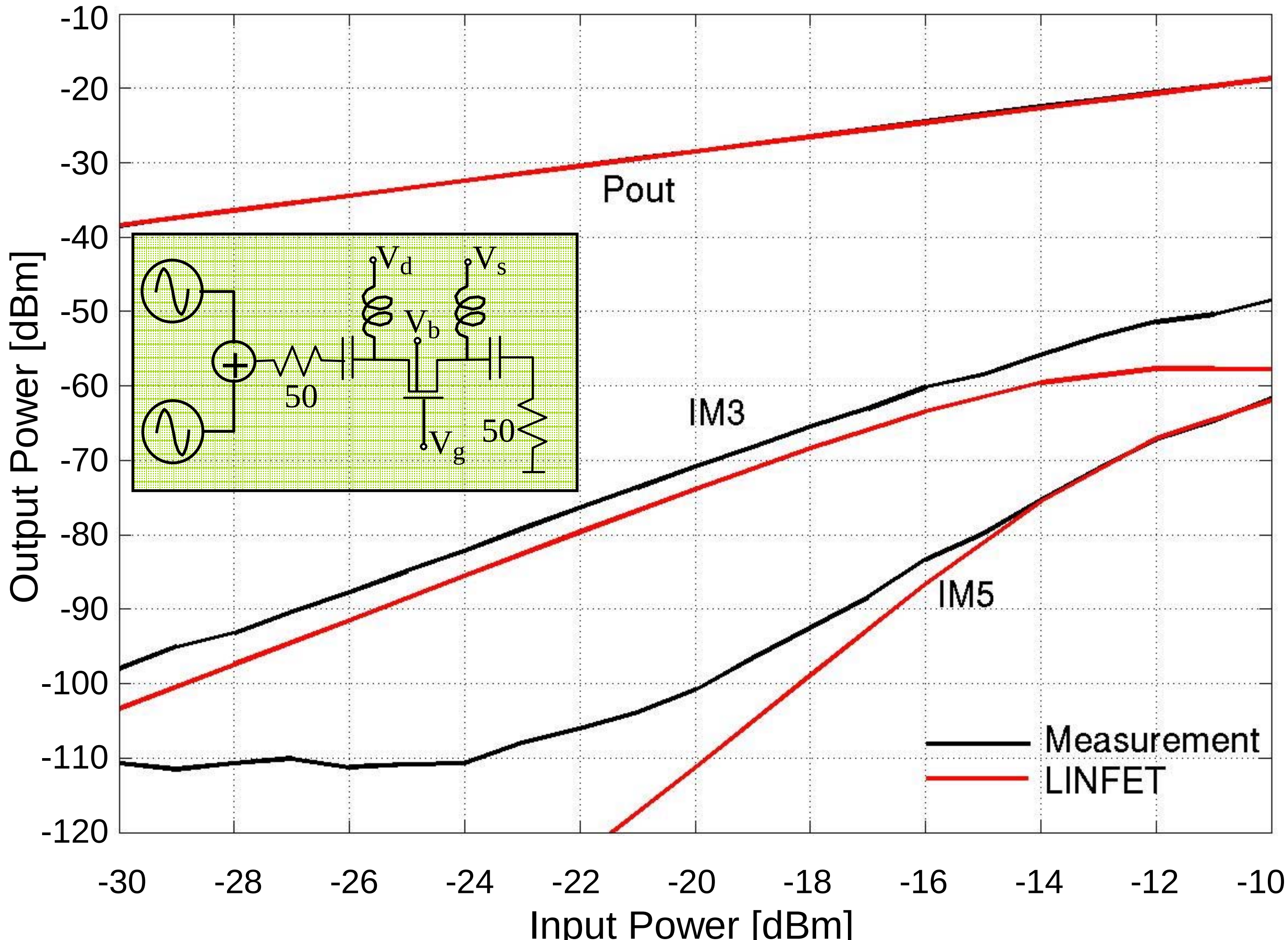

Nfet
Vd = 1.8
Vd = 0.05
Data
Linfet Model
Id (A)
Vg (volts)


Nfet
Data
Linfet Model
Vg = 1.8
Vg = 1.2
Id (A)
Vx (volts)

Gummel symmetry test for a 0.18x10um NFET.
a) IV, b) 1st derivative, c) 2nd derivative, d) 3rd derivative.



Distortion in the 3rd (IM3) and 5th (IM5) intermodulation products for a passive mixer configuration.



LINFET capacitance formulation

- **Charges retain dependence on V_{gst} and V_{gdt} .**

$$Q_c = \int_0^L q_c(y)dy = -\frac{2}{3}C_{ox}L\frac{V_{gst}^3 - V_{gdt}^3}{V_{gst}^2 - V_{gdt}^2} = -\frac{2}{3}C_{ox}L\left(\frac{V_{gst}^2 + V_{gst}V_{gdt} + V_{gdt}^2}{V_{gst} + V_{gdt}}\right)$$

$$Q_g = \int_0^L q_g(y)dy = \frac{C_{ox}L}{(1+\alpha)}\left\{\alpha\left(V_{gb} - V_{t0} + 2V_{bi}\right) + \frac{2}{3}\left(\frac{V_{gst}^2 + V_{gst}V_{gdt} + V_{gdt}^2}{V_{gst} + V_{gdt}}\right)\right\}$$

$$Q_b = \int_0^L q_b(y)dy = -\frac{\alpha C_{ox}L}{(1+\alpha)}\left\{\left(V_{gb} - V_{t0} + 2V_{bi}\right) - \frac{2}{3}\left(\frac{V_{gst}^2 + V_{gst}V_{gdt} + V_{gdt}^2}{V_{gst} + V_{gdt}}\right)\right\}$$

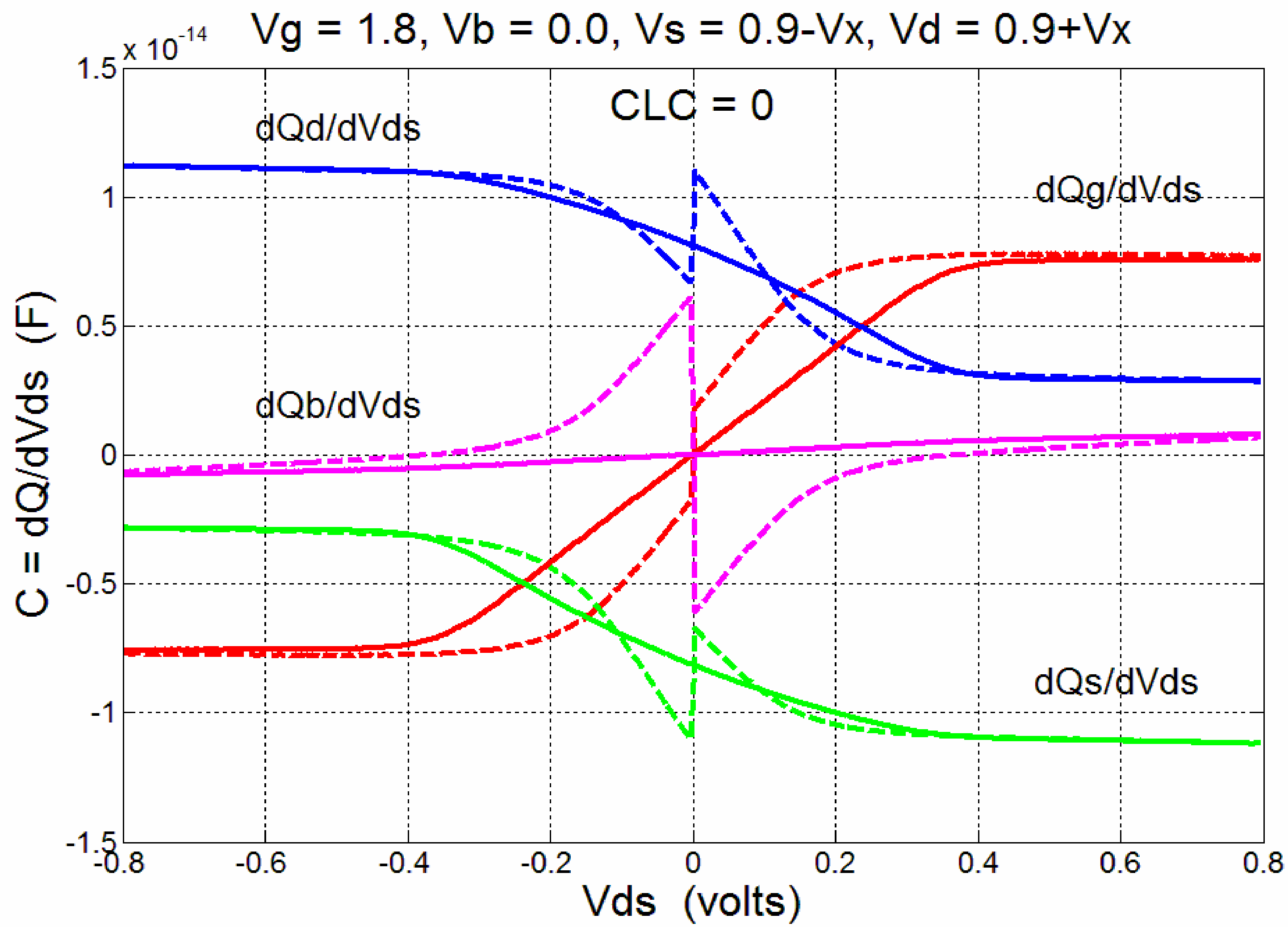
LINFET capacitance formulation (continued)

- **Source/Drain charges with 40/60 partitioning.**

$$Q_s = \int_0^L q_c(y)\left(1-\frac{y}{L}\right)dy = -\frac{2}{15}C_{ox}L\left[\frac{3V_{gst}^3+6V_{gst}^2V_{gdt}+4V_{gst}V_{gdt}^2+2V_{gdt}^3}{\left(V_{gst}+V_{gdt}\right)^2}\right]$$

$$Q_d = \int_0^L q_c(y)\left(\frac{y}{L}\right)dy = -\frac{2}{15}C_{ox}L\left[\frac{2V_{gst}^3+4V_{gst}^2V_{gdt}+6V_{gst}V_{gdt}^2+3V_{gdt}^3}{\left(V_{gst}+V_{gdt}\right)^2}\right]$$

Derivatives of gate, source, drain and body charges. Dashed lines: BSIM model. Solid lines: LINFET model.



Conclusions

- **The LINFET model removes all the discontinuities in the derivatives of current and charge at V_{ds}=0.**
  - This result is possible because source/drain symmetry is maintained throughout the model derivation.
  - The derivation parallels that of BSIM so that many of the parameters from existing BSIM models may be reused. Only a minor recentering of the model is necessary.
  - We have shown good agreement between model and hardware up to the third derivative of the drain to source current.

