Lecture 28 - The "Long" Metal-Oxide-Semiconductor Field-Effect Transistor *(cont.)*

April 18, 2007

Contents:

1. Second-order and non-ideal effects

Reading assignment:

del Alamo, Ch. 9, §9.7

Key questions

- The potential of the inversion layer increases along the channel. This should change the *local* threshold voltage. Does this affect the I-V characteristics of the MOSFET?
- What happens to MOSFET I-V characteristics if we apply a bias to the body with respect to the source?

1. Second-order and non-ideal effects in MOSFETs

Introduce four significant refinements to model:

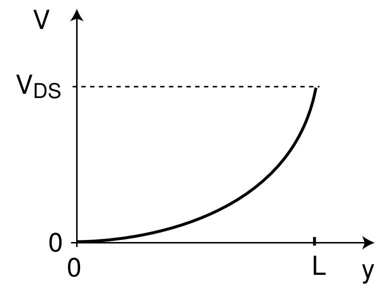
- Body effect (impact of y-dependence of V_T)
- Back bias (impact of V_{BS})
- Channel length modulation (impact of $V_{DS} > V_{DSsat}$)
- Subthreshold regime (channel conduction for $V_{GS} < V_T$)

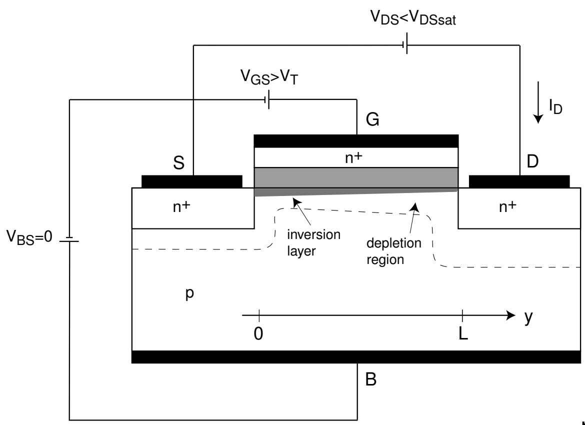
□ Body effect

In a MOSFET biased in linear or saturation regimes, channel voltage $V(y)$ depends on position:

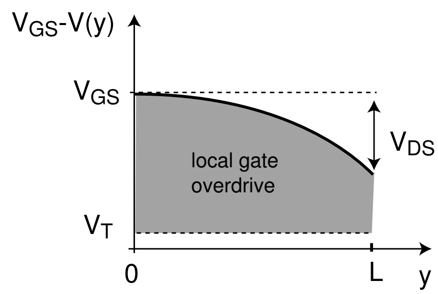
$\Rightarrow$ voltage difference between channel and body $V(y)$

$\Rightarrow V_T(y)$ (increases along y)

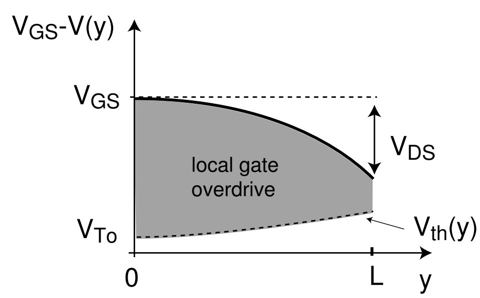




no body effect



with body effect



Dependence of $V_T(y)$ further debiases transistor:

$\Rightarrow I_D$ lower than ideal

$\Rightarrow V_{DSsat}$ lower than ideal

Voltage dependence of V_T:

$$V_T(V) = V_{To} + \gamma(\sqrt{\phi_{sth} + V} - \sqrt{\phi_{sth}})$$

V_{To} is V_T for $V_{SB} = 0$.

Charge control relation becomes:

$$Q_i = -C_{ox}(V_{GS} - V - V_T) = -C_{ox}[V_{GS} - V - V_{To} - \gamma(\sqrt{\phi_{sth} + V} - \sqrt{\phi_{sth}})]$$

Insert into current equation:

$$I_e = W \mu_e Q_i \frac{dV}{dy} = -W \mu_e C_{ox}[V_{GS} - V - V_{To} - \gamma(\sqrt{\phi_{sth} + V} - \sqrt{\phi_{sth}})] \frac{dV}{dy}$$

Integrate from $y = 0$ to $y = L \Rightarrow$ MOSFET current in linear regime:

$$I_D = \frac{W}{L} \mu_e C_{ox} \{(V_{GS} - V_{To} + \gamma\sqrt{\phi_{sth}} - \frac{1}{2} V_{DS}) V_{DS} - \frac{2}{3}\gamma[(\phi_{sth} + V_{DS})^{3/2} - (\phi_{sth})^{3/2}]\}$$

Note new terms multiplied by $\gamma \Rightarrow$ if $\gamma \rightarrow 0$, body effect $\rightarrow 0$.

To get V_{DSsat}, look at Q_i at $y = L$:

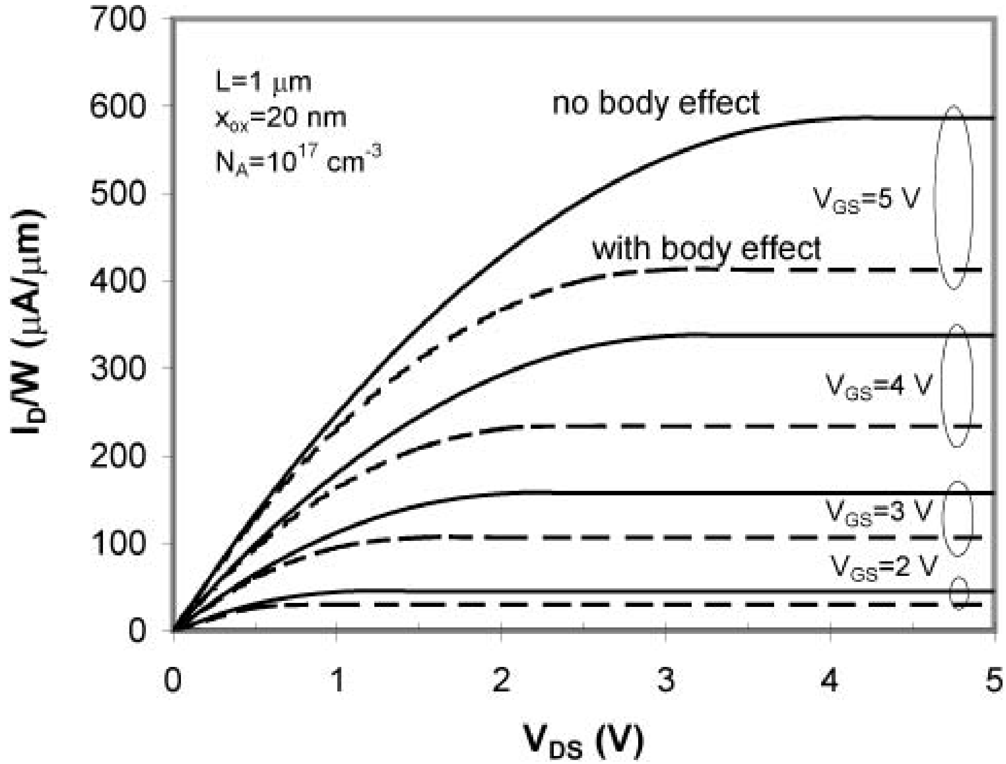
$$Q_i(y = L) = -C_{ox}[V_{GS} - V_{DSsat} - V_{To} - \gamma(\sqrt{\phi_{sth} + V_{DSsat}} - \sqrt{\phi_{sth}})] = 0$$

Solve for V_{DSsat}:

$$V_{DSsat} = V_{GS} - V_{To} + \gamma\sqrt{\phi_{sth}} - \frac{\gamma^2}{2}[\sqrt{1 + \frac{4}{\gamma^2}(V_{GS} - V_{FB})} - 1]$$

MOSFET saturated current: plug V_{Dssat} into current equation in linear regime:

$$I_{Dsat} = \frac{W}{L}\mu_e C_{ox}\{(V_{GS} - V_{To} + \gamma\sqrt{\phi_{sth}} - \frac{1}{2}V_{DSsat})V_{DSsat}$$
$$-\frac{2}{3}\gamma[(\phi_{sth} + V_{DSsat})^{3/2} - (\phi_{sth})^{3/2}]\}$$

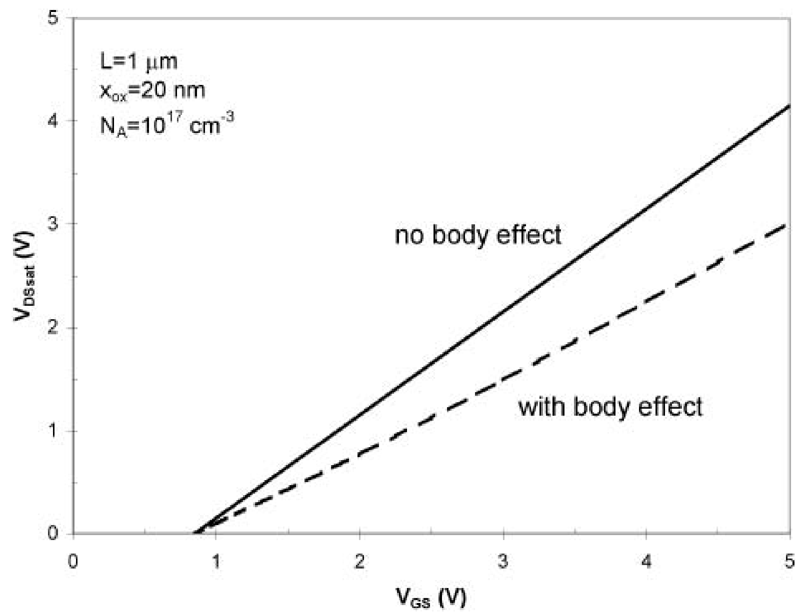


Three noticeable features:

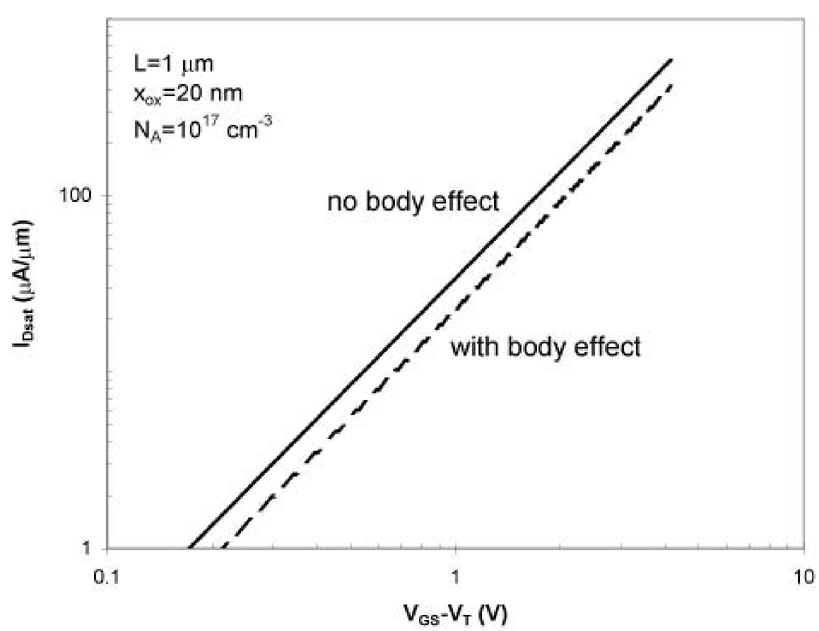
- for all values of V_{GS} and V_{DS}, body effect reduces I_D
- for given V_{GS}, body effect reduces V_{DSsat}
- body effect goes away as transistor is turned off

Key observations for model simplification:

- V_{DSssat} dependence on V_{GS} remains roughly linear:



- I_{Dsat} dependence on V_{GS} remains roughly quadratic:



Linearize dependence of V_T on V ($V \ll \phi_{sth}$):

$$V_T(V) = V_{To} + \gamma(\sqrt{\phi_{sth} + V} - \sqrt{\phi_{sth}}) \simeq V_{To} + \frac{\gamma}{2\sqrt{\phi_{sth}}}V$$

Solve again differential equation to get MOSFET current in linear regime:

$$I_D \simeq \frac{W}{L}\mu_e C_{ox}(V_{GS} - V_{To} - \frac{m}{2}V_{DS})V_{DS}$$

with:

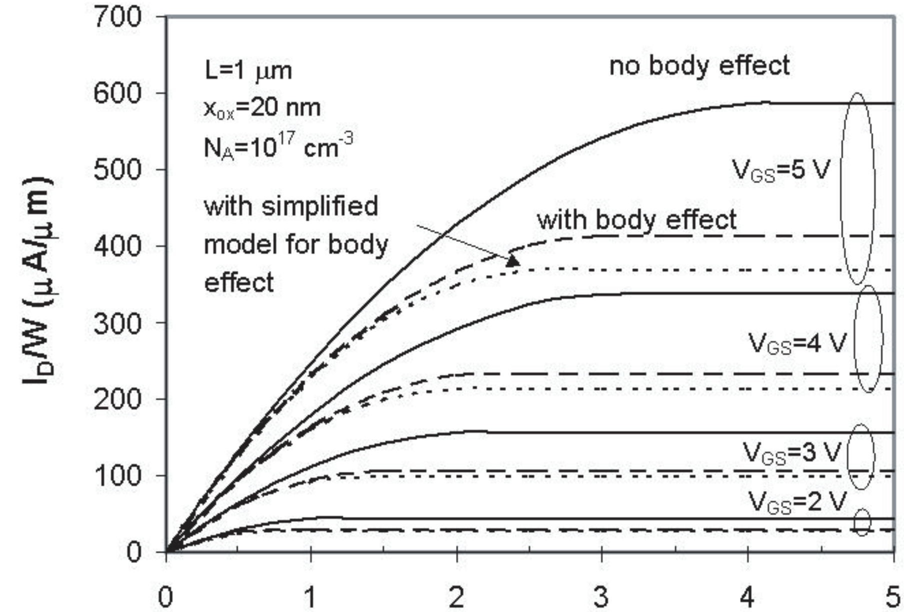
$$m = 1 + \frac{\gamma}{2\sqrt{\phi_{sth}}} > 1$$

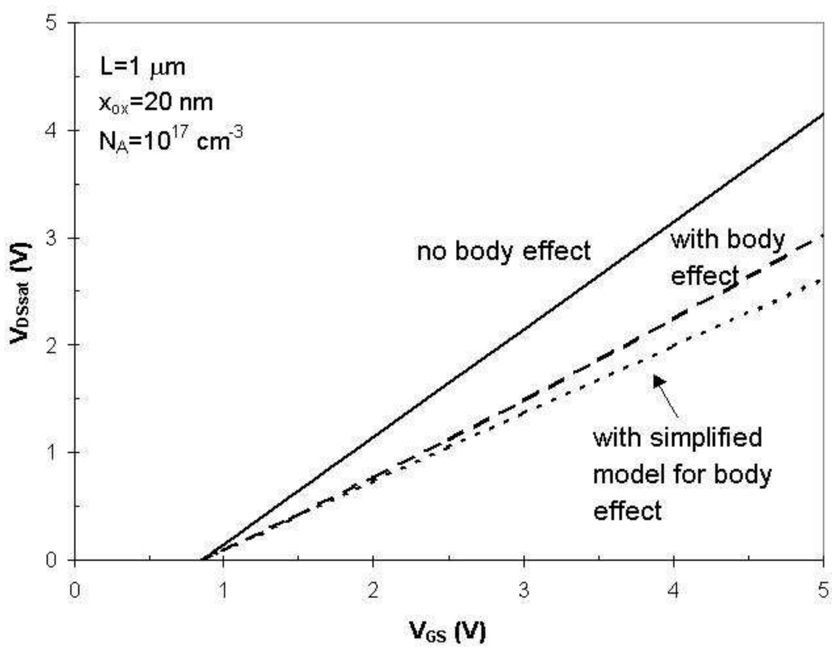
V_{DSsat} becomes:

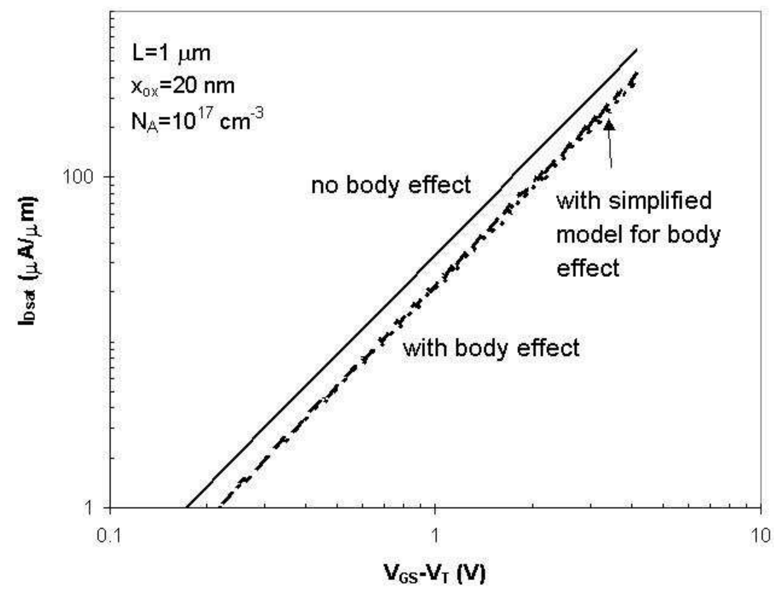
$$V_{DSsat} \simeq \frac{1}{m}(V_{GS} - V_{To})$$

Current in saturation regime:

$$I_{Dsat} \simeq \frac{W}{2mL}\mu_e C_{ox}(V_{GS} - V_{To})^2$$


L=1 μm
x_ox=20 nm
N_A=10^17 cm^-3
with simplified model for body effect
no body effect
with body effect
V_GS=5 V
V_GS=4 V
V_GS=3 V
V_GS=2 V
I_D/W (μA/μm)
0
100
200
300
400
500
600
700
0
1
2
3
4
5


L=1 μm
x_ox=20 nm
N_A=10^17 cm^-3
no body effect
with body effect
with simplified model for body effect
V_DSsat (V)
V_GS (V)
0
1
2
3
4
5



m is *body-effect coefficient* $(m > 1)$:

$$m = 1 + \frac{\gamma}{2\sqrt{\phi_{sth}}}$$

m has same dependences as γ:

- $x_{ox} \downarrow \Rightarrow \ \gamma \downarrow \Rightarrow m \downarrow$ (less severe body effect)
- $N_A \uparrow \Rightarrow \ \gamma \uparrow \Rightarrow m \uparrow$ (more severe body effect)

m and γ represent relative electrostatic influence of gate and body on inversion layer; if $\gamma = 0 \rightarrow \ m = 1$ (negligible impact of body).

In circuit CAD, m used as fitting parameter. Typically $m \sim 1.1 - 1.4$.

□ Back bias

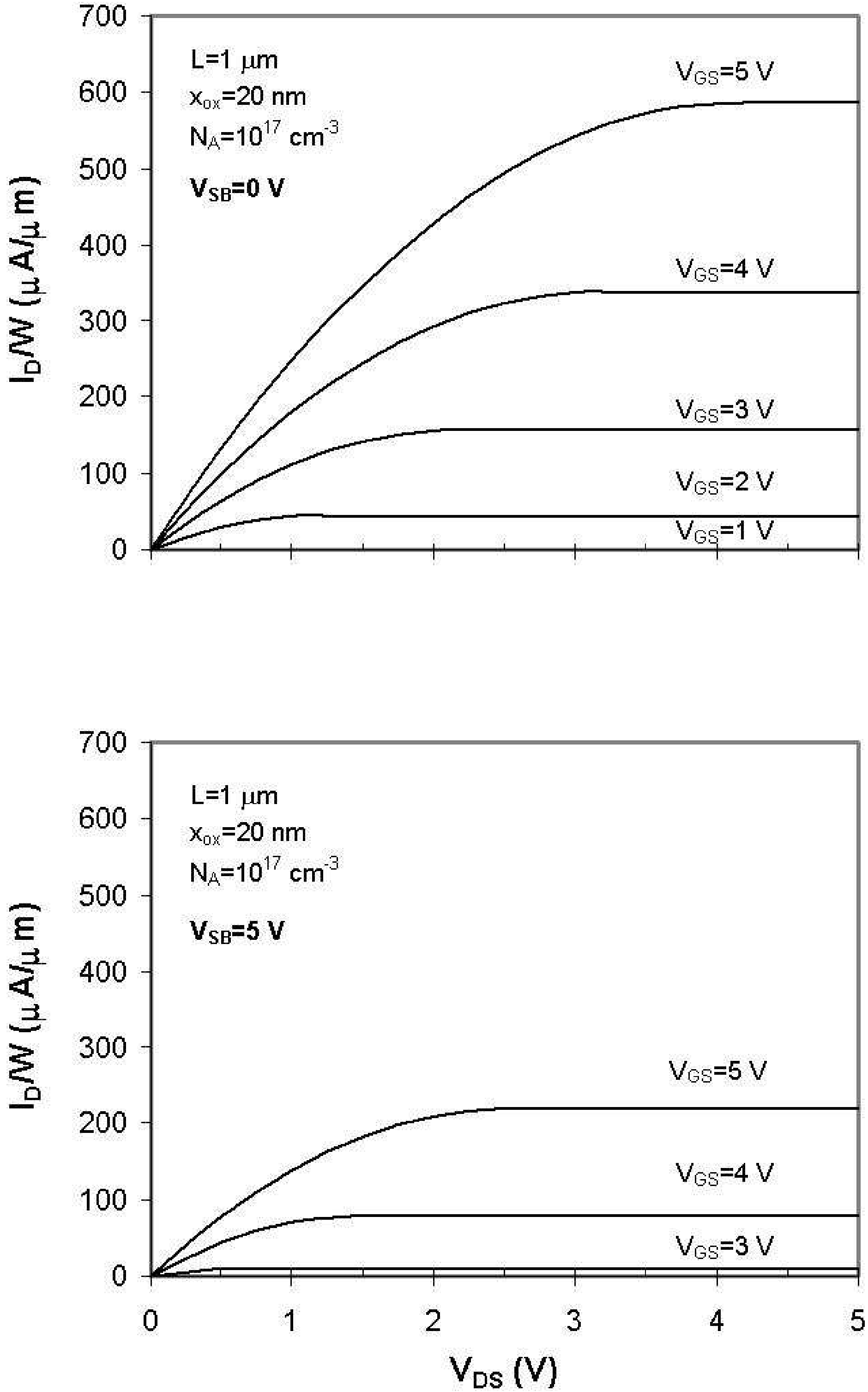
If bias applied to body with respect to source ($V_{SB} > 0$):

$\Rightarrow V_T$ shifts positive

$\Rightarrow$ for constant V_{GS} and V_{DS}, I_D reduced

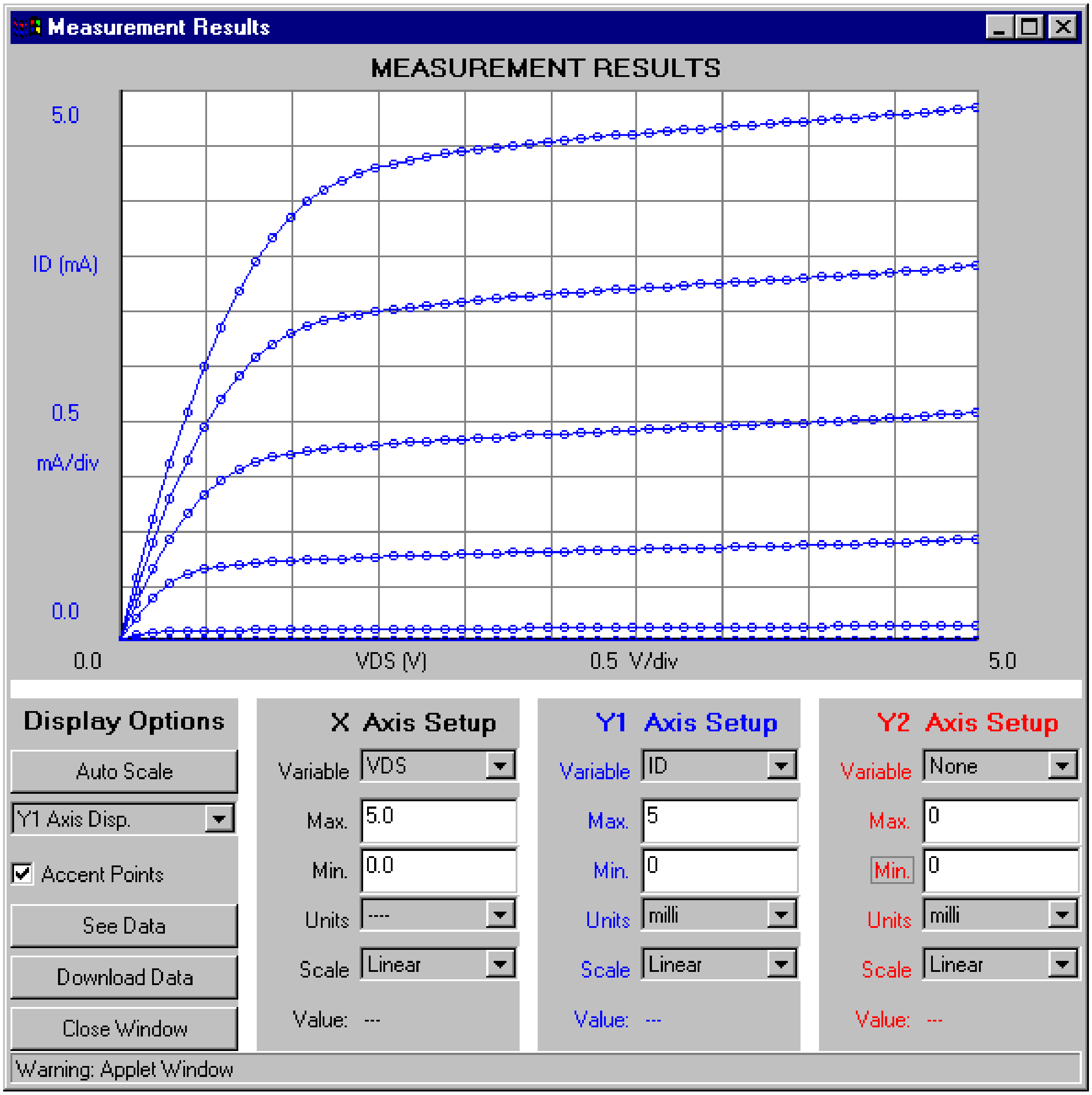
Model in absence of body effect $\Rightarrow$ just replace V_T in first order model by:

$$V_T(V_{SB}) = V_{To} + \gamma(\sqrt{\phi_{sth} + V_{SB}} - \sqrt{\phi_{sth}})$$

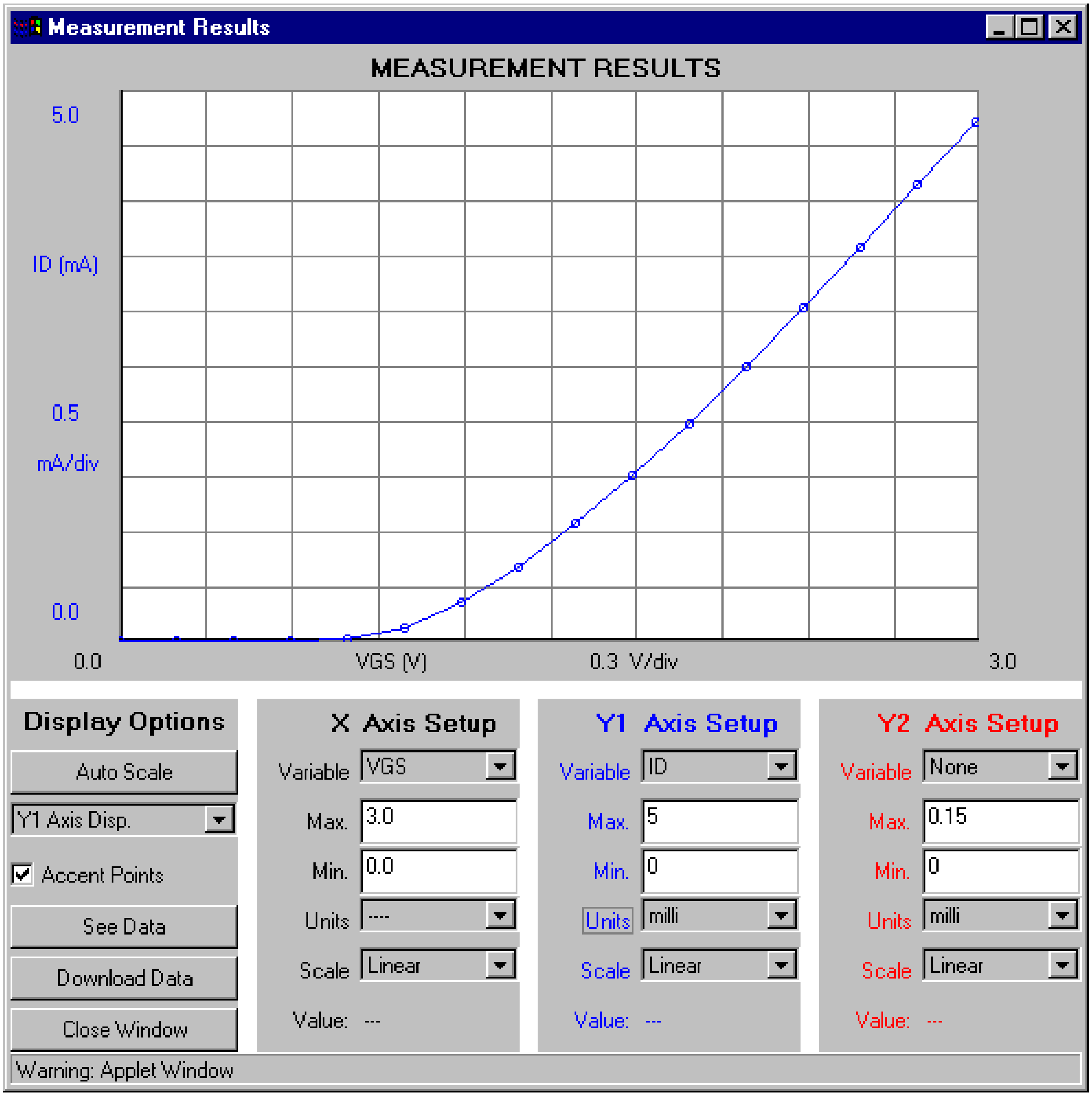

700
600
500
400
300
200
100
0
L=1 μm
x_ox=20 nm
N_A=10^17 cm^-3
V_SB=0 V
V_GS=5 V
V_GS=4 V
V_GS=3 V
V_GS=2 V
V_GS=1 V
I_D/W (μA/μm)
700
600
500
400
300
200
100
0
L=1 μm
x_ox=20 nm
N_A=10^17 cm^-3
V_SB=5 V
V_GS=5 V
V_GS=4 V
V_GS=3 V
I_D/W (μA/μm)
0
1
2
3
4
5
V_DS (V)

I-V characteristics of n-channel MOSFET ($L = 1.5\ \mu m$)

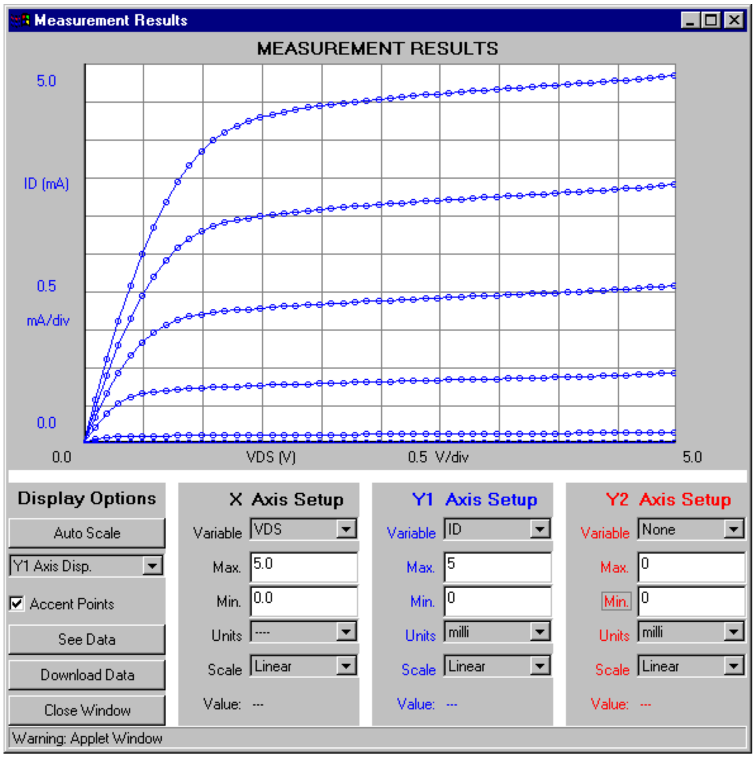
☐ Output characteristics ($V_{GS} = 0 - 3\ V$, $\Delta V_{GS} = 0.5\ V$):

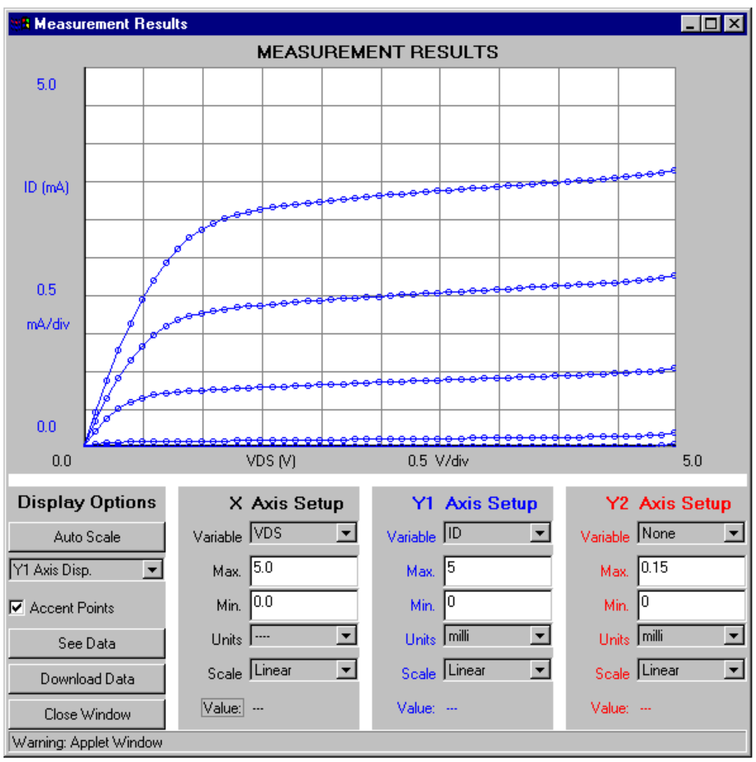


□ Transfer characteristics ($V_{DS} = 4\ V$):

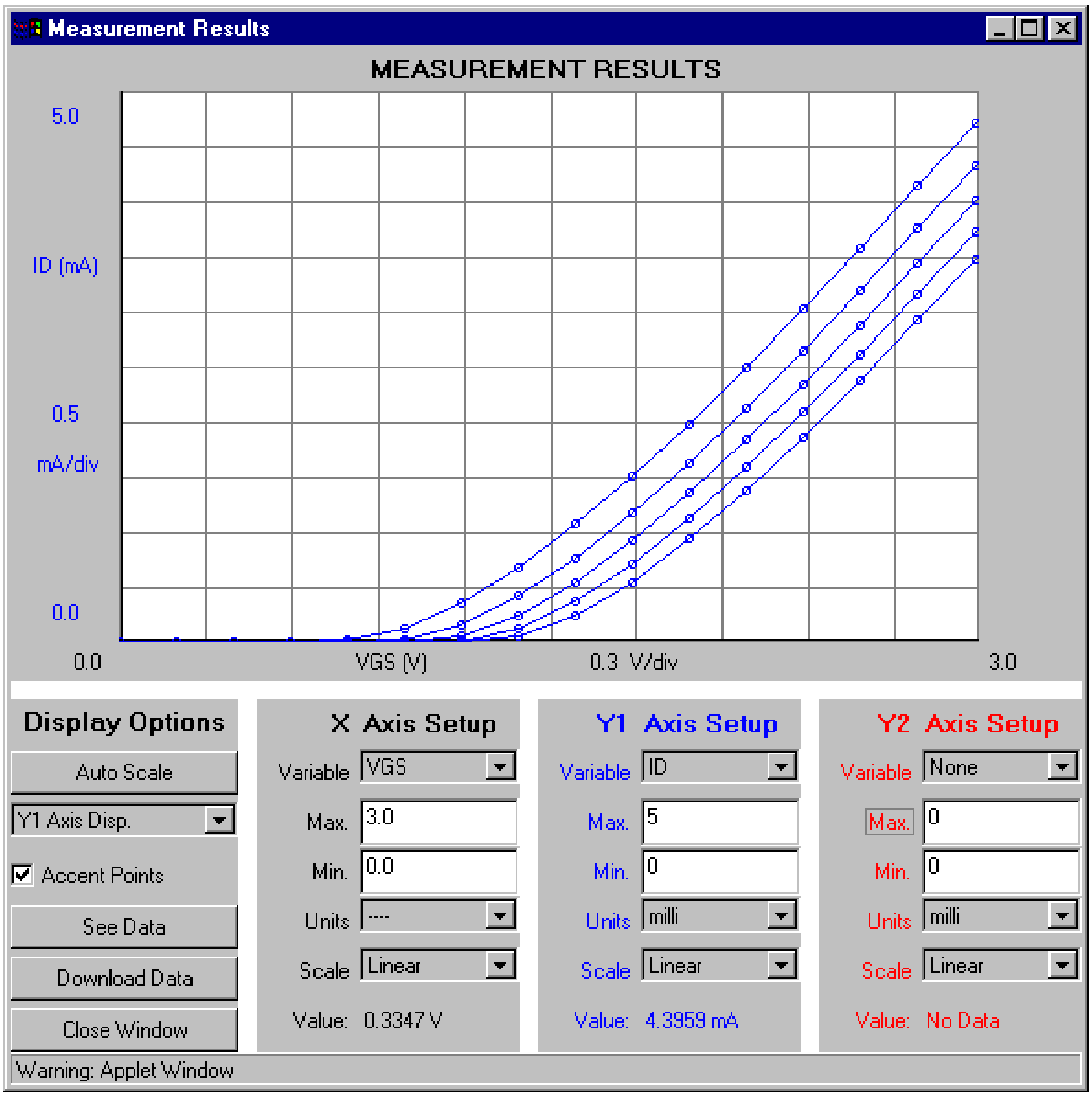


□ Output characteristics vs. back bias ($V_{SB} = 0,\ 2\ V$):

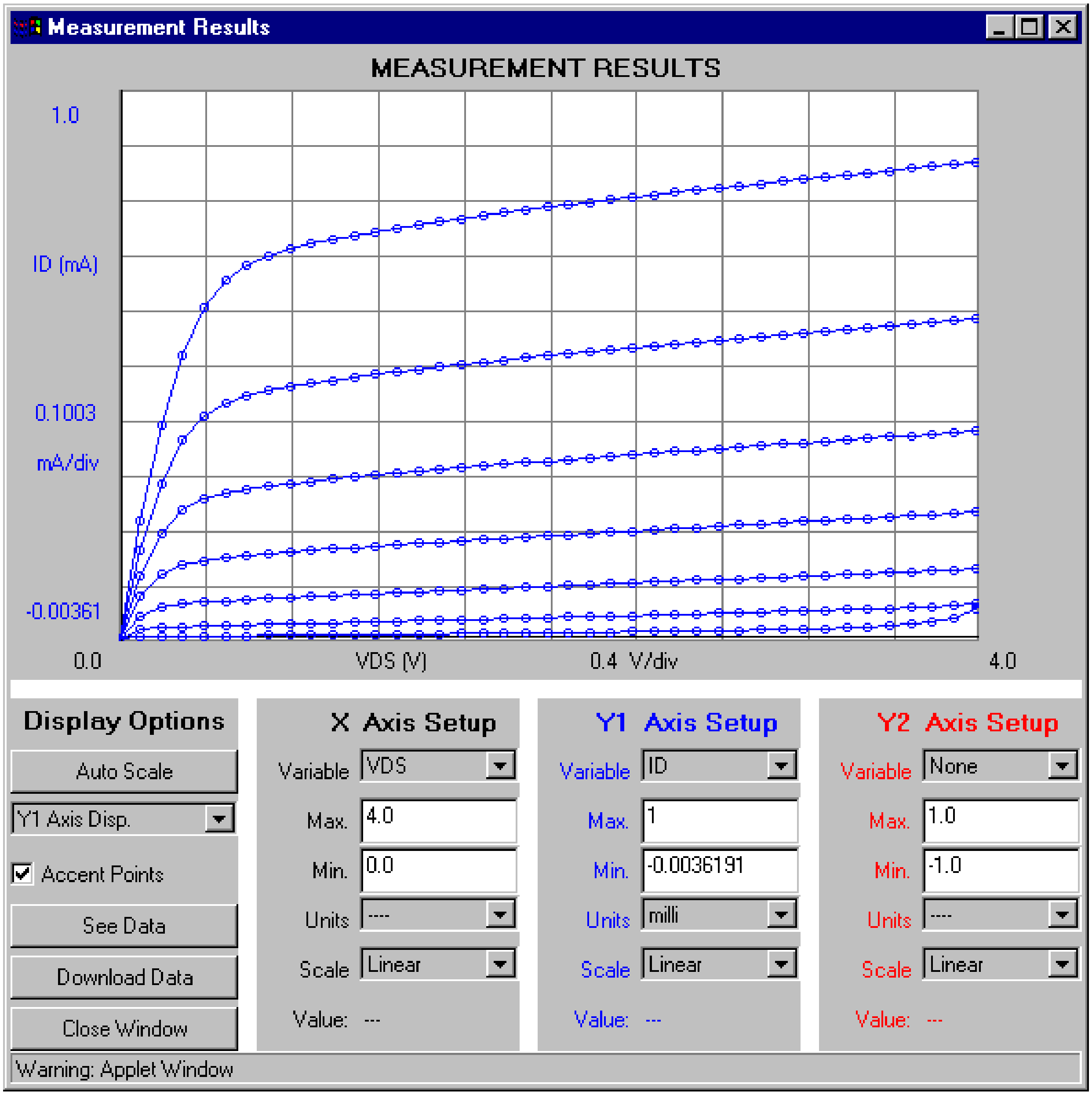




□ Transfer characteristics vs. back bias ($V_{DS} = 4\ V$, $V_{SB} = 0 - 2\ V$, $\Delta V_{SB} = 0.5\ V$):



□ Backgate output characteristics ($V_{SB} = 0 - 3\ V$ in 0.5 V increments, $V_{GS} = 1.5\ V$):



Key conclusions

- "Body effect" arises from spatial dependence of V_T: local gate overdrive reduced.
- Main consequences of body effect:
  - I_D lower than ideal,
  - V_{DSsat} lower than ideal.
- Simple formulation of body effect is fairly accurate:

$$I_{Dsat} \simeq \frac{W}{2mL}\mu_e C_{ox}(V_{GS} - V_{To})^2$$

  with $m \geq 1$.
- m captures relative electrostatic influence of gate and body (want $m \to 1$).
- Application of back bias shifts V_T positive and reduces I_D.