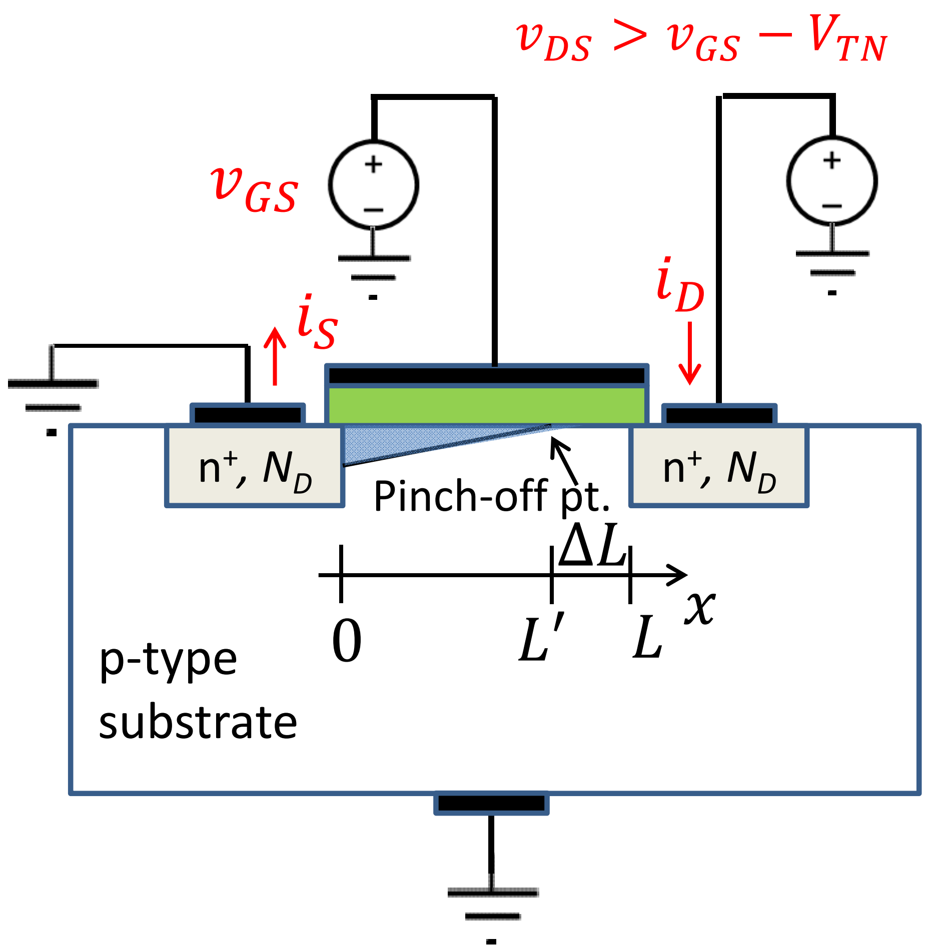
Announcements

- HW 4 due today.
  - For P1, can assume VFB=0.
  - Can hand in at end of class or by 3pm at my office.
- Exam 1: mean = 52, median=53.5, σ = 16.
  - Most problem with Problem 2
  - Likely a multi-diode problem on final

Channel-length Modulation

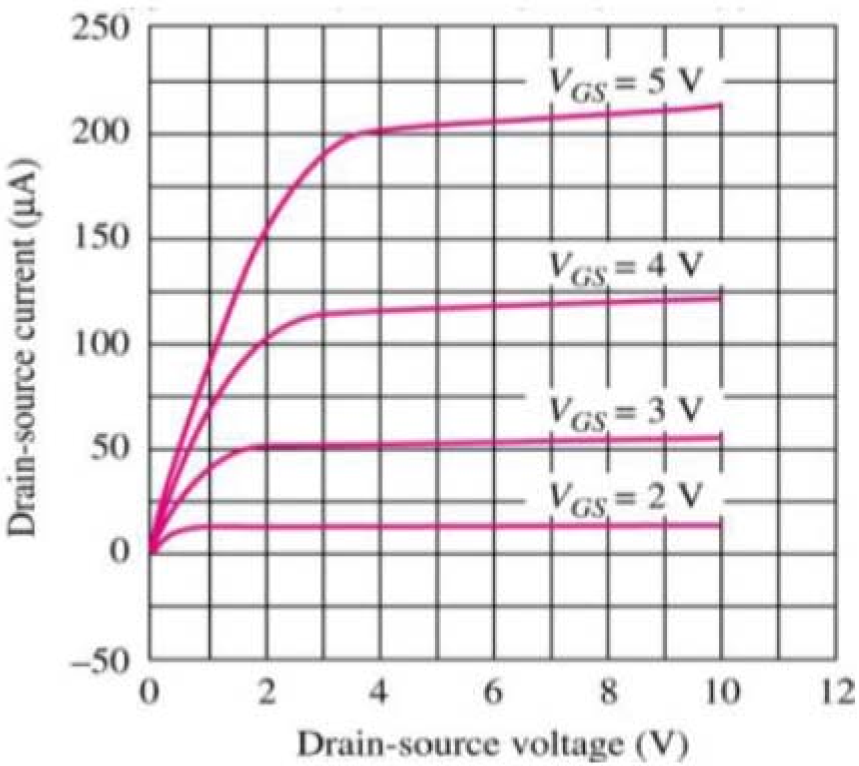


- In saturation, the channel length also decreases as v_{DS} increases.
- This causes the channel current to slightly increase as v_{DS} increases.
- This dependence is modeled heuristically by

$$L' = {}^{L}\!/\!\left(1 + \lambda(v_{DS} - v_{DSat})\right)$$

$$i_D = \frac{K'_n}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 \left(1 + \lambda(v_{DS} - v_{DSat})\right)$$

Channel Length Modulation



- $i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 \times (1 + \lambda(v_{DS} - v_{DSat}))$
- λ: channel-length modulation parameter, typically in the range of $10^{-3}\mathrm{V}^{-1} \le \lambda \le 10^{-1}\mathrm{V}^{-1}$

NMOS Operation Regions (Text)

Operation Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} < V_{TN}$
Triode	$i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$	$v_{GS} > V_{TN}$ $v_{GS} - v_{DS} \geq V_{TN}$
Saturation	$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 (1 + \lambda v_{DS})$	$v_{GS} > V_{TN}$ $v_{GS} - v_{DS} < V_{TN}$

Channel Length Modulation

Body Effect:

$$V_{TN} = V_{TO} + \gamma\left(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F}\right)$$

NMOS Operation Regions (Correct)

Operation Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} < V_{TN}$
Triode	$i_D = K'_n \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$	$v_{GS} > V_{TN}$ $v_{GS} - v_{DS} \geq V_{TN}$
Saturation	$i_D = \frac{K'_n}{2}\frac{W}{L}(v_{GS} - V_{TN})^2[1 + \lambda(v_{DS} - v_{DSat})]$	$v_{GS} > V_{TN}$ $v_{GS} - v_{DS} < V_{TN}$

Channel Length Modulation

Body Effect:

$$V_{TN} = V_{TO} + \gamma(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

NMOS Operation Regions (Alternative)

Operation Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} \leq V_{TN}$
Triode	$i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}\ (1 + \lambda v_{DS})$	$v_{GS} > V_{TN}$ $v_{GS} - V_{TN} > v_{DS}$
Saturation	$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 (1 + \lambda v_{DS})$	$v_{GS} > V_{TN}$ $v_{GS} - V_{TN} \leq v_{DS}$

Channel Length Modulation

Body Effect:

$$V_{TN} = V_{TO} + \gamma(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

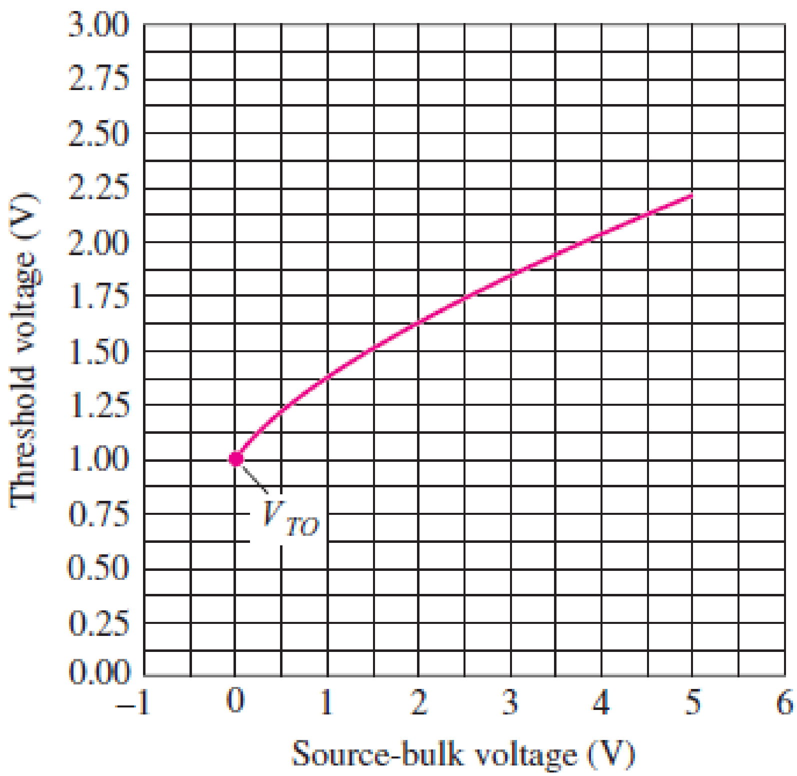
Body Effect (Substrate Sensitivity)

- A nonzero value of v_{SB} changes the value of the threshold voltage:

$$V_{TN} = V_{TO} + \gamma(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

  - V_{TO}: zero-substrate-bias value for V_{TN} (V)
  - γ: body-effect parameter ($\sqrt{\mathrm{V}}$)
  - $2\phi_F$: surface potential parameter (V).
  - $2\phi_F = 2(kT/q)\ln(N_{sub}/ni)$ (built-in voltage for diode with doping of $N_A = ND = Nsub$).

Body Effect (Substrate Sensitivity)



$$V_{TN} = V_{TO} + \gamma\left(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F}\right)$$