4530, Lecture 4

Summary

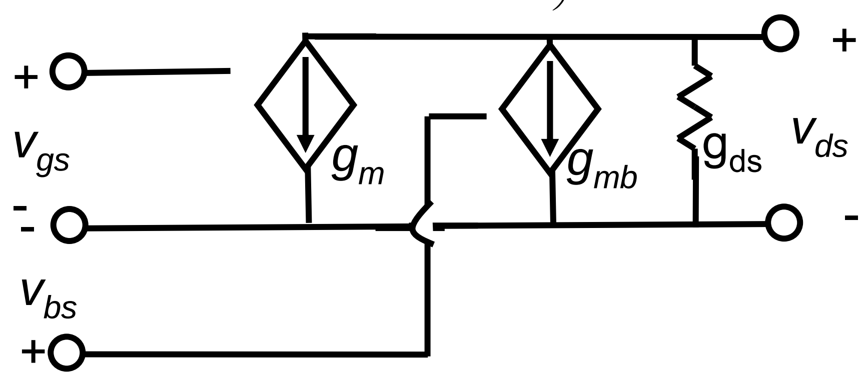
Body effect

- Bulk ("Body", "Backgate") acts as a second gate on channel
  - V_{BS} affects V_{TH}: $V_{TH} = V_{TH0} + \gamma\left(\sqrt{|2\Phi_F - V_{BS}|} - \sqrt{|2\Phi_F|}\right)$
    - (note book uses V_{SB}, so sign is inverted)
  - For small signal model, can treat as a second transconductance, g_{mb}

$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} = \frac{\partial}{\partial V_{BS}}\left(\frac{W}{L}\mu_n c_{ox}\frac{\left(V_{GS} - V_{TH0} - \gamma\left(\sqrt{|2\Phi_F - V_{BS}|} - \sqrt{|2\Phi_F|}\right)\right)^2}{2}\right)$$

$$g_{mb} = g_m\left(\frac{\gamma}{2\sqrt{|2\Phi_F - V_{BS}|}}\right)$$

  - Usually $g_{mb} \approx 0.1 g_m$



Channel length modulation

- Under saturation
  - Higher V_{DS} increases pinch-off region
  - Effectively shorter channel:

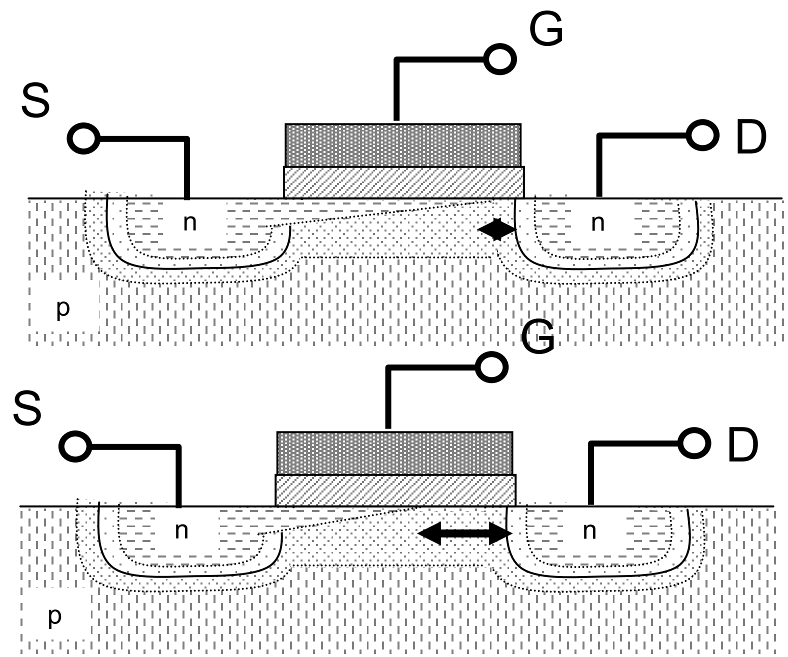
$$L_{eff} = L - L_{pinch} = L(1-\lambda V_{DS}) \approx \frac{L}{1+\lambda V_{DS}}$$

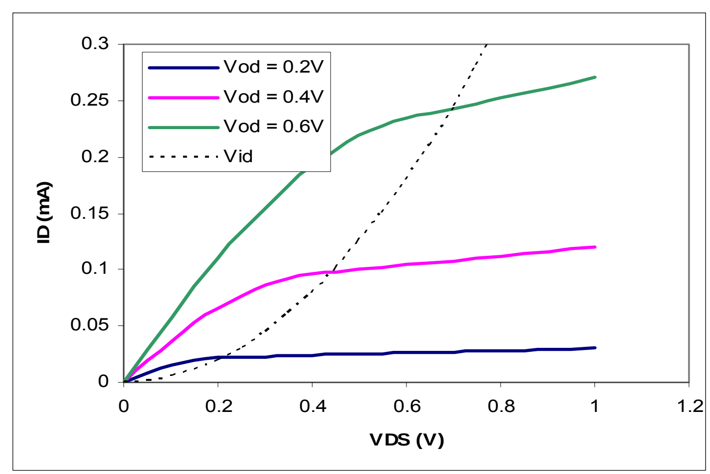
$$I_D = \frac{W}{L_{eff}} \mu_n c_{ox} \frac{(V_{GS}-V_{TH})^2}{2}$$

$$I_D = \frac{W}{L} \mu_n c_{ox} \frac{(V_{GS}-V_{TH})^2}{2} (1+\lambda V_{DS})$$

$$g_{ds} = \frac{W}{L} \mu_n c_{ox} \frac{(V_{GS}-V_{TH})^2}{2} \lambda \approx \lambda I_D$$

$$r_o = \frac{1}{g_{ds}} \approx \frac{1}{\lambda I_D}$$





Note that λ is inversely proportional to L

Sub-threshold and velocity Saturation

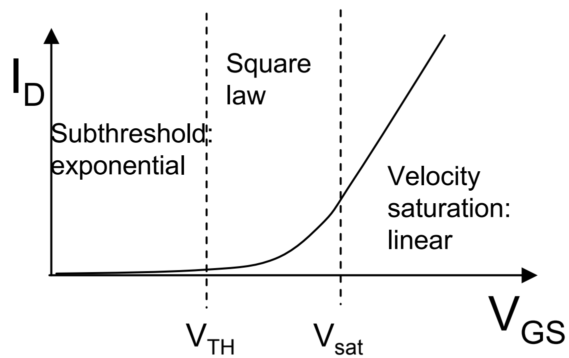
- For $V_{GS}<V_{TH}+100mV$
  - Square law breaks down
- For $V_{GS}<V_{TH}-100mV$
  - Exponential:

$$I_D = I_o e^{V_{GS}/\varsigma V_T}$$

$$\varsigma V_T \approx 35mV (\varsigma \approx 1.25)$$

$$gm = \frac{I_o}{\varsigma V_T} e^{V_{GS}/\varsigma V_T} = \frac{I_D}{\varsigma V_T}$$

- In between smooth switch from square to exponential:
- but the math is a mess



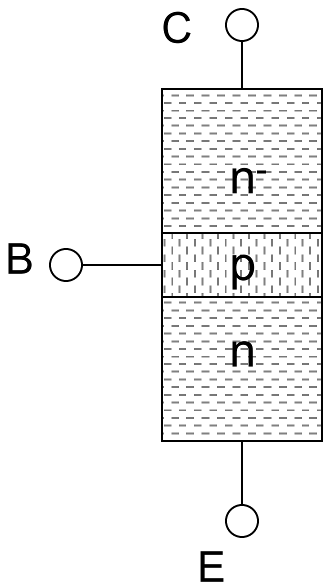
- For short channels, large VGS, VDS
  - Electron velocity "saturates":
  - Current not proportional to electric field
  - Response becomes linear (not square)

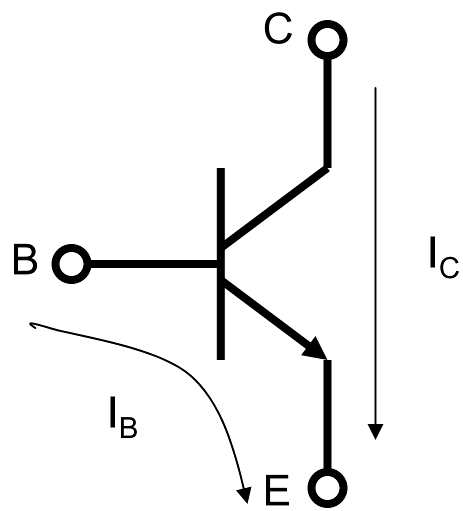
$$I_D = k(V_{GS} - V_{TH})$$

$$gm = k$$

  - "k" = $W/L\mu c_{ox}V_{sat}$ where V_{sat} is the voltage where velocity saturation kicks in

BJTs



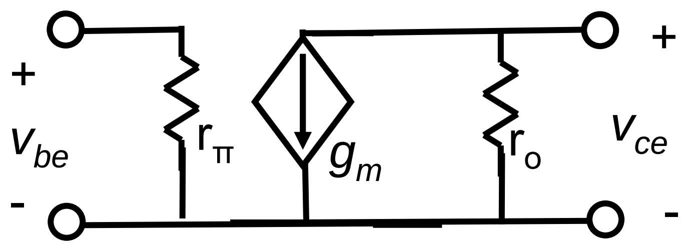


Provided in forward active (V_{CE}>0.2V)

$$I_C = I_o e^{V_{BE}/V_T}\left(1+\frac{V_{CE}}{V_A}\right)$$

$$I_B = \frac{I_o}{\beta} e^{V_{BE}/V_T} \approx \frac{I_C}{\beta}$$

as $V_{CE}\rightarrow 0$, base-collector junction turns on, Beta decreases



$$g_m = \frac{\delta I_C}{\delta V_{BE}} = \frac{I_o e^{V_{BE}/V_T}}{V_T}\left(1+\frac{V_{CE}}{V_A}\right) = \frac{I_C}{V_T}$$

$$r_\pi = \left(\frac{\delta I_B}{\delta V_{BE}}\right)^{-1} = \left(\frac{I_o}{V_T\beta} e^{V_{BE}/V_T}\right)^{-1} \approx \frac{\beta}{g_m}$$

$$r_o = \left(\frac{\delta I_C}{\delta V_{CE}}\right)^{-1} = \left(\frac{I_o}{V_A\beta} e^{V_{BE}/V_T}\right)^{-1} \approx \frac{I_C}{V_A}$$

Common Source Amplifier

- In saturation:

$$V_{out} = VDD - R_L I_D = VDD - R_L \frac{W}{L} \mu_n c_{ox} \frac{(V_{in} - V_{TH})^2}{2}$$

- Choose W/L, V_{in} to set I_D, stay in saturation
  - For saturation, choose bias:

$$I_D \times R_L < VDD - V_{OD}$$

$$remember, V_{OD} = V_{GS} - V_{TH}$$

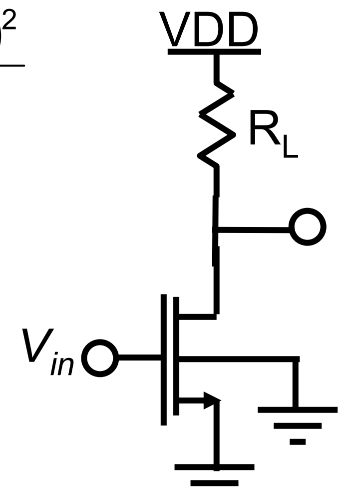
- now can calculate gain:

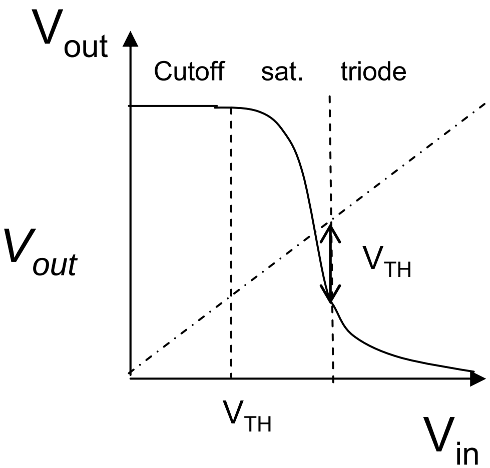
$$A = -g_m \cdot (R_L \parallel r_o)$$

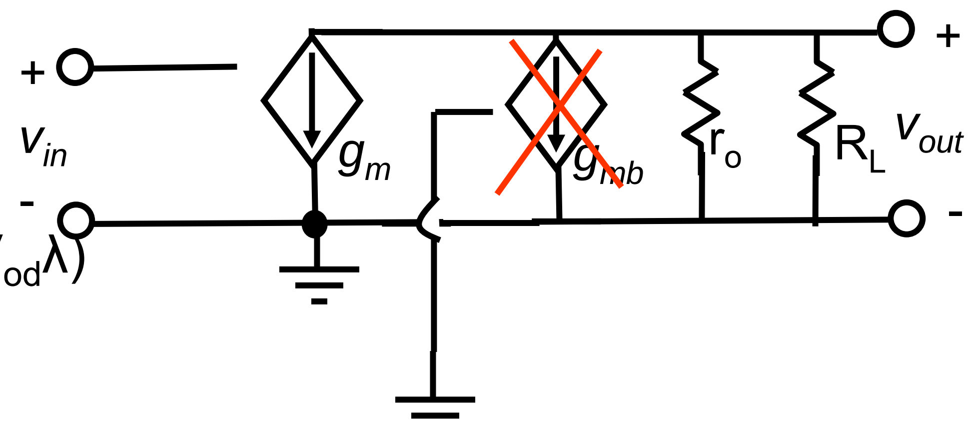
- For square law:

$$A = \frac{-2I_D}{V_{OD}} (R_L \parallel r_o) \approx \frac{-2I_D R_L}{V_{OD}}$$

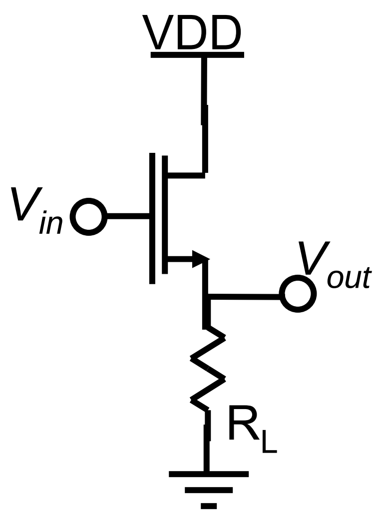
- Max gain $R_L \rightarrow >> ro$
- A= $-g_m r_o$ (square law: $A=-2/(V_{od}\lambda)$)

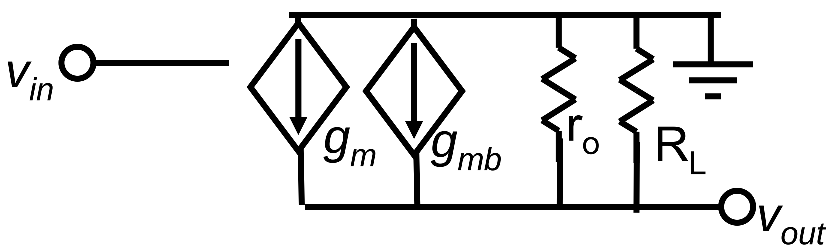






Source Follower (common Drain)





- If bulk grounded:

$$A = \frac{g_m}{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_L}} \xrightarrow{R_L \to \infty} \frac{g_m}{g_m + g_{mb} + \frac{1}{r_o}} \approx 0.9$$

$$Z_{out} = \frac{1}{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_L}} \xrightarrow{R_L \to \infty} \frac{1}{g_m + g_{mb} + \frac{1}{r_o}} \approx \frac{1.1}{g_m}$$

- If bulk tied to source:

$$A = \frac{g_m}{g_m + \frac{1}{r_o} + \frac{1}{R_L}} \xrightarrow{R_L \to \infty} \frac{g_m}{g_m + \frac{1}{r_o}} \approx 1$$

$$Z_{out} = \frac{1}{g_m + \frac{1}{r_o} + \frac{1}{R_L}} \xrightarrow{R_L \to \infty} \frac{1}{g_m + \frac{1}{r_o}} \approx \frac{1}{g_m}$$