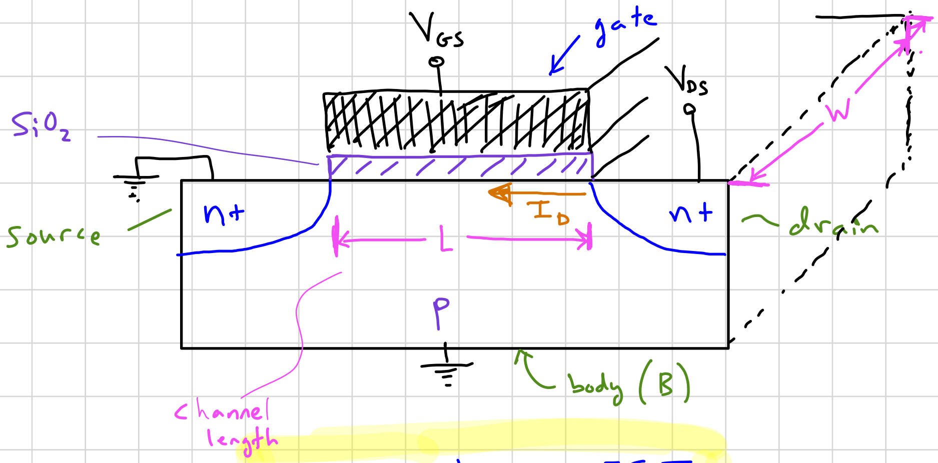
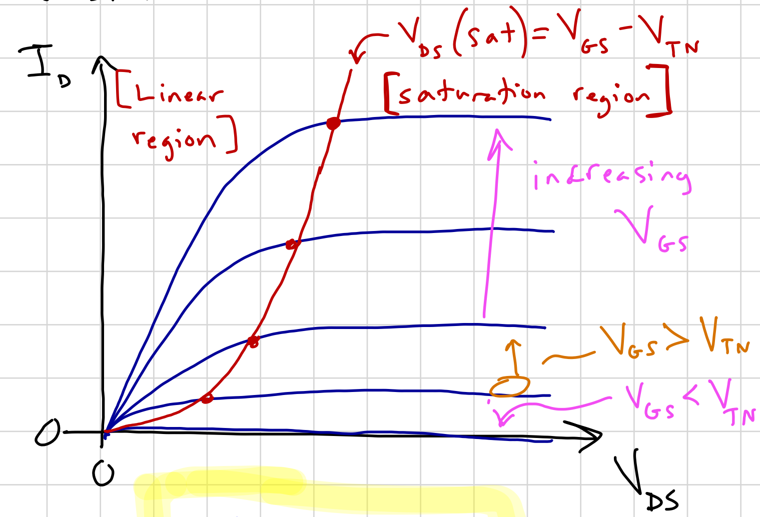
Lecture #14

MOSFETs - Basic operation

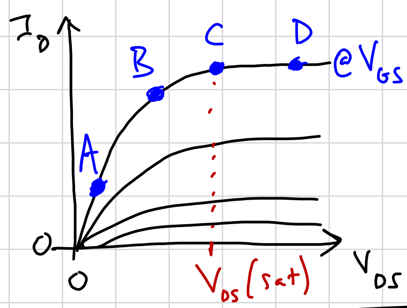
Recall:
- MOSFET is a switch that is turned on/off by gate voltage (V_{GS})
- MOS capacitor is core of MOSFET and determines on-state (threshold voltage) → V_T
- Drain voltage (V_{DS}) determines operating regime in on-state



n-channel MOSFET (nMOS)



Output curves (I_D - V_{DS})



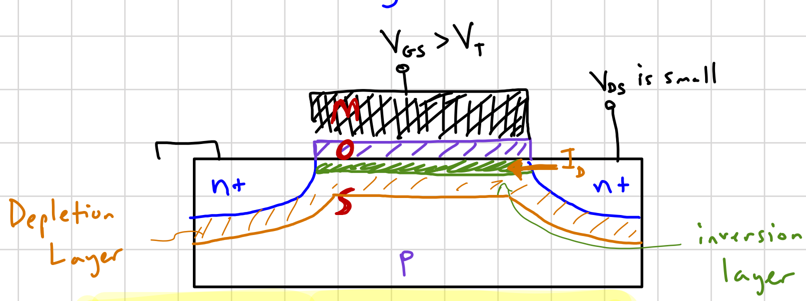
Linear Region

at A $V_{GS} > V_T$, V_{DS} is small

→ inversion layer is formed in channel, connecting source & drain

→ applied V_{DS} creates $\mathcal{E}$-field to generate

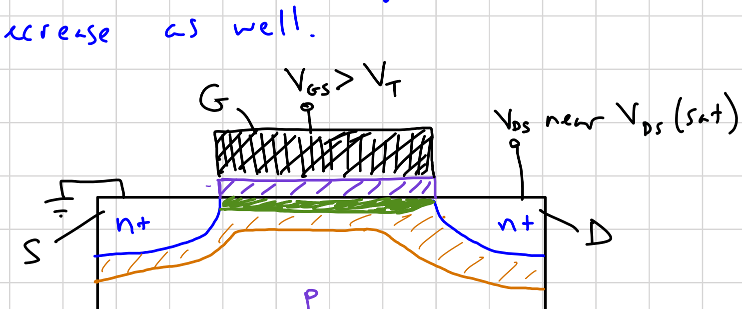
e^-s ← current flowing from source to drain



$$I_D = \frac{W \mu_n C_{ox}}{L}(V_{GS} - V_T)V_{DS}$$ (linear portion of linear region)

at B $V_{GS} > V_T$, V_{DS} close to $V_{DS}(sat)$

→ Voltage drop across oxide (band movement at Si-SiO_2 interface) decreases near drain, causing inversion charge near drain to decrease as well.

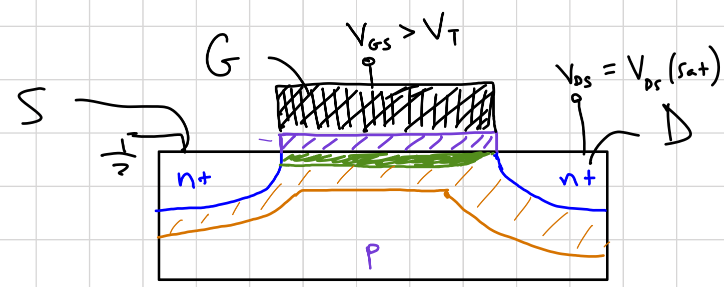


$$I_D = \frac{W \mu_n C_{ox}}{2L}\left[2\underbrace{(V_{GS} - V_T)}_{V_{DS}(sat)}V_{DS} - V_{DS}^2\right]$$ anywhere in linear region

Saturation Region

at C $V_{GS} > V_T$, $V_{DS} = V_{DS}(sat)$

→ inversion charge density becomes zero at drain, "pinching off" inversion channel

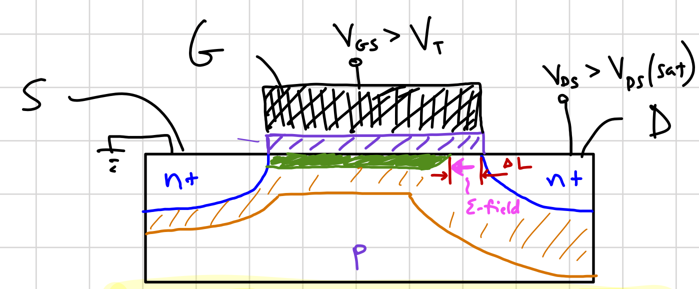


at D $V_{GS} > V_T$, $V_{DS} > V_{DS}(sat)$

→ "pinched off" region of L (ΔL) becomes larger and corresponding $\mathcal{E}$-field in the ΔL region becomes larger

→ e^-s are swept across ΔL by $\mathcal{E}$-field

→ If $\Delta L \ll L$, then I_D is constant

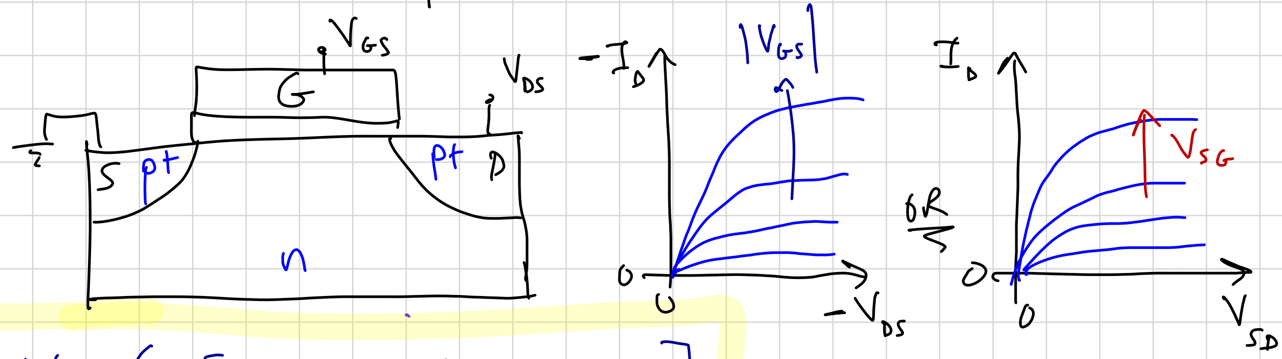


$$I_D = \frac{W \mu_n C_{ox}}{2L}(V_{GS} - V_T)^2 = I_D(sat)$$

$K_n \equiv$ conduction parameter

$K_n' = \mu_n C_{ox} \equiv$ process conduction parameter

For a p-channel MOSFET:



Linear: $I_D = \frac{W\mu_p C_{ox}}{2L}\left[2(V_{SG}+V_T)V_{SD} - V_{SD}^2\right]$

Saturation: $I_D = \frac{W\mu_p C_{ox}}{2L}(V_{SG}+V_T)^2 = I_D(sat)$

$K_p = \frac{W\mu_p C_{ox}}{2L}$

$k_p' = \mu_p C_{ox}$

Transconductance (AKA, transistor gain)

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{W\mu_n C_{ox}}{L}(V_{GS}-V_T)$$

for sat. region

Substrate Bias effects (see book)

→ Applying a V_{BS} to the body (B) will shift V_T such that:

$$\Delta V_T = V_T(V_{SB}>0) - V_T(V_{SB}=0) = \underbrace{\frac{\sqrt{2e\epsilon_s\epsilon_0 N_a}}{C_{ox}}}_{\gamma}\left[\sqrt{2\phi_{fp}+V_{SB}} - \sqrt{2\phi_{fp}}\right]$$

$\gamma \equiv$ body-effect coefficient

Enhancement vs. Depletion mode

↳ @ $V_{GS}=0$, no inversion layer (MOSFET is off)

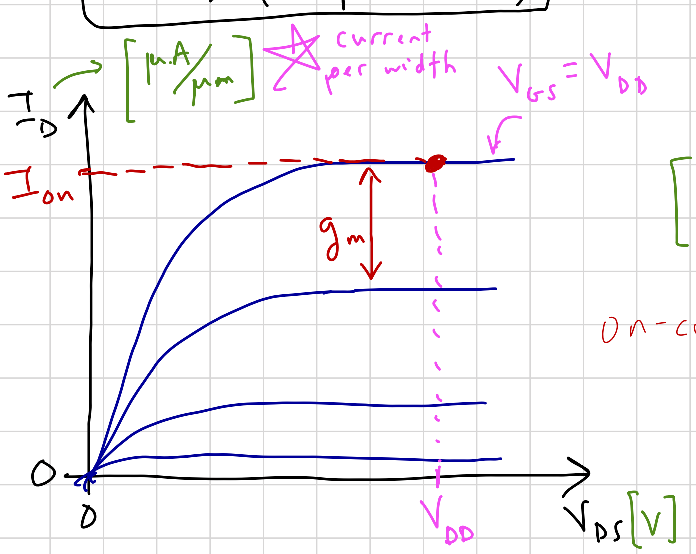
↳ @ $V_{GS}=0$, there is an inversion layer, so device is already ON and must apply V_{GS} to turn it OFF

[Note: $V_{DD} \equiv$ operating voltage
↳ $V_{GS} = V_{DS} = V_{DD}$]

I-V curves and relevant performance metrics for MOSFETs

ON-STATE

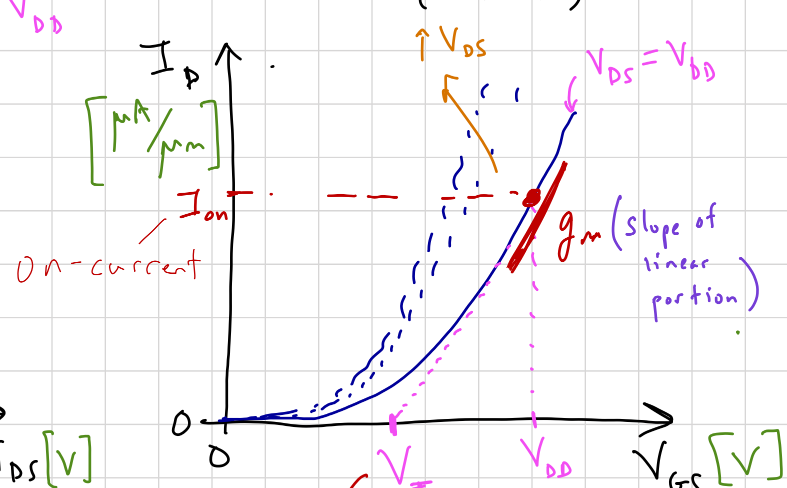
I_D-V_{DS} (output curves)



mobility: $\mu = \frac{g_m L^2}{V_{DS} C_{ox}}$

I_D-V_{GS} (transfer curves)

(LINEAR)



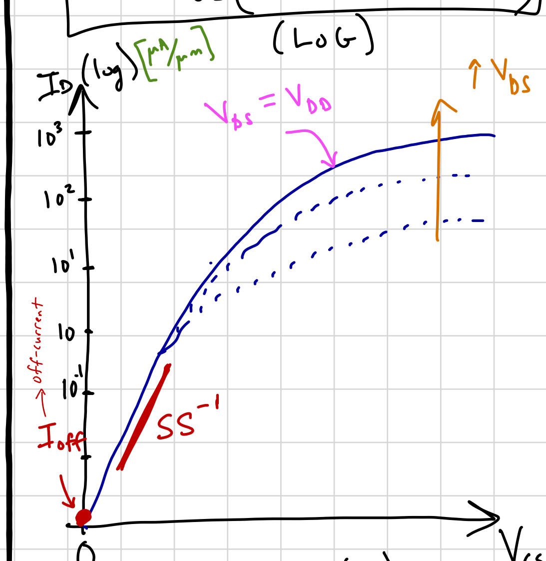
linear extrapolation from linear portion gives V_T

$g_m = \frac{dI_D}{dV_{GS}}$

OFF-state

I_D-V_{GS} (subthreshold curves)

(LOG)



Subthreshold Swing (SS):

$$SS = \left(\frac{d(\log(I_D))}{dV_{GS}}\right)^{-1} \doteq 60\ mV/dec$$

→ how many mV of V_{GS} to change I_D by one decade (order of magnitude)

Best possible "thermal limit"