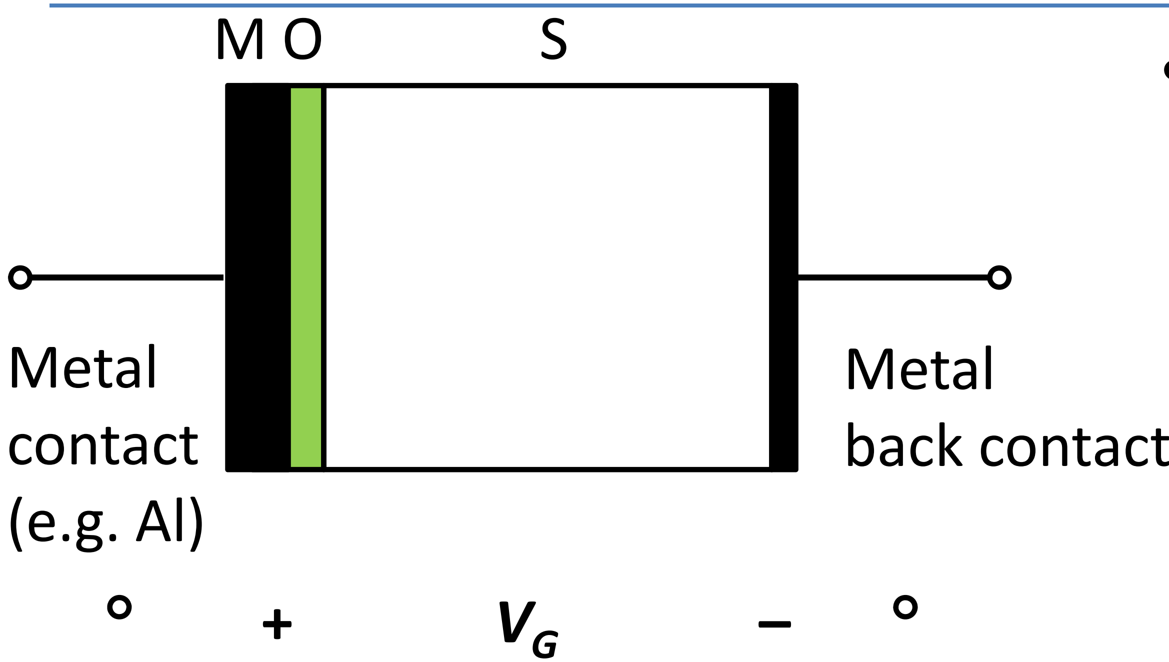
Announcements

- HW 4 posted, due Friday (May 2)
- Exams returned later this week.

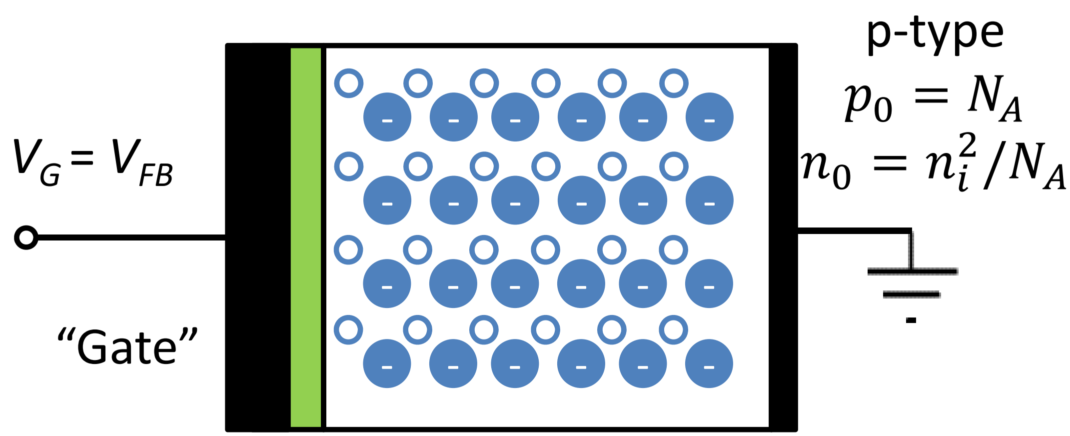
MOS Capacitor



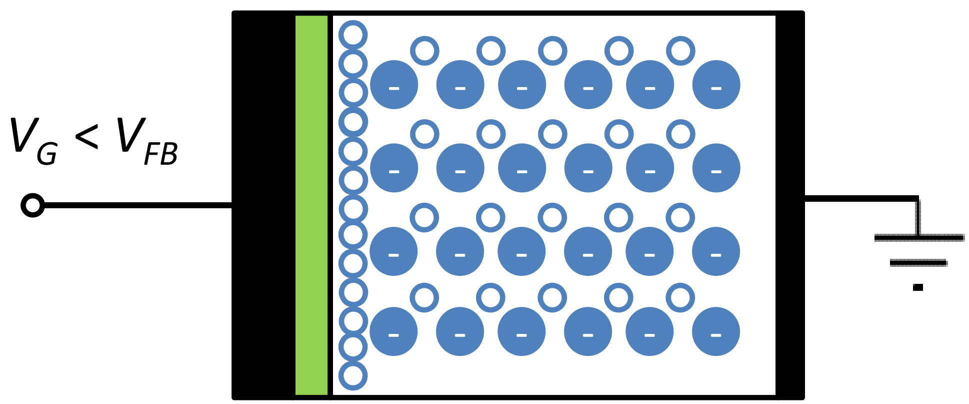
- Built-in voltage just like pn junction --- electrons shift to material with lower energy until balance reached.

- When external voltage is applied, electrons are attracted to higher voltage (+) and holes are attracted to lower voltage (-)
- Oxide layer blocks electrons or holes (isolation)

MOS Capacitor Physics (p-Si)



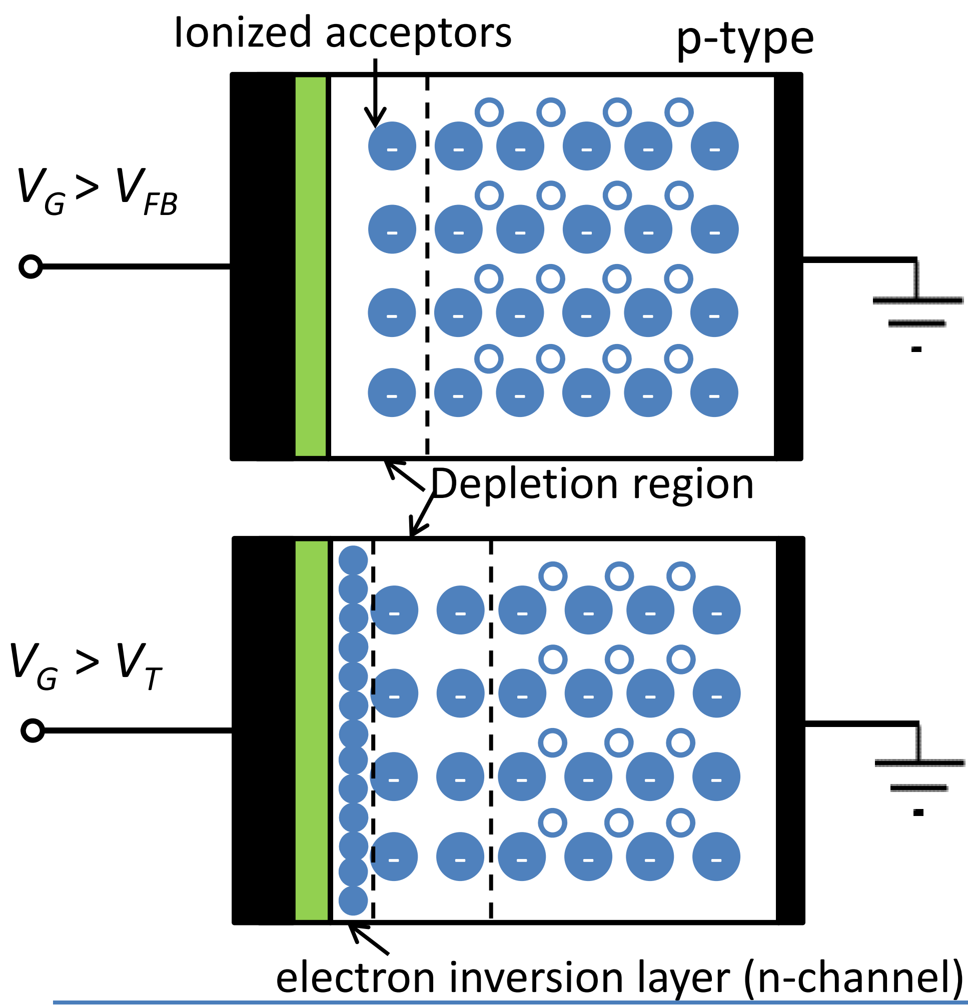
Flat Band ($V_{FB} = \Phi_{BI}$)
When $V_G = V_{FB}$, hole concentration in Si equals doping (no net charge)



accumulation layer of holes

$V_G < V_{FB}$, holes attracted to the gate side, but blocked by the oxide layer => accumulation of holes in semiconductor near interface with oxide.

MOS Capacitor Physics (p-Si)

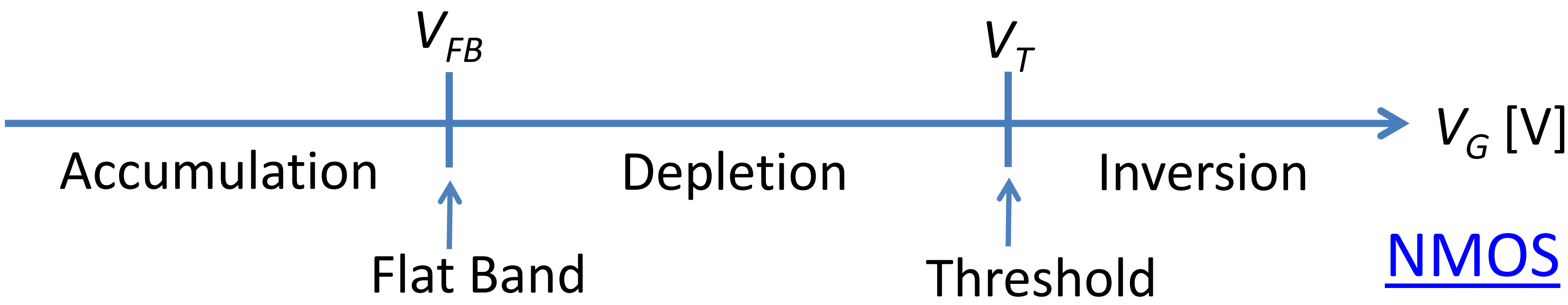


$V_G > V_{FB}$, holes repelled from the O-S interface => Depletion of holes in semiconductor near the interface with oxide.

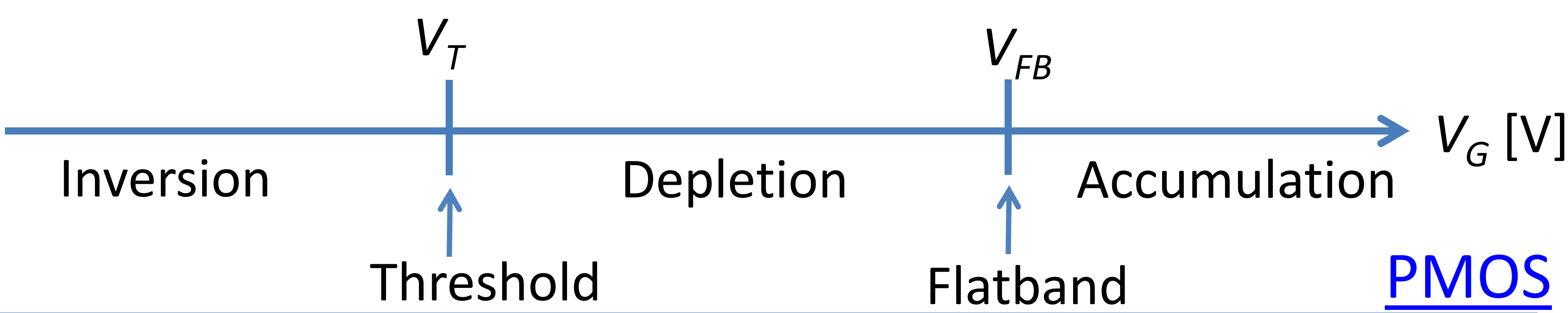
Further increasing V_G to $V_G > V_T$, electrons generated and attracted to the interface become the majority carrier => electron inversion layer formed in semiconductor just beneath the interface w/ oxide

MOS Capacitor Physics

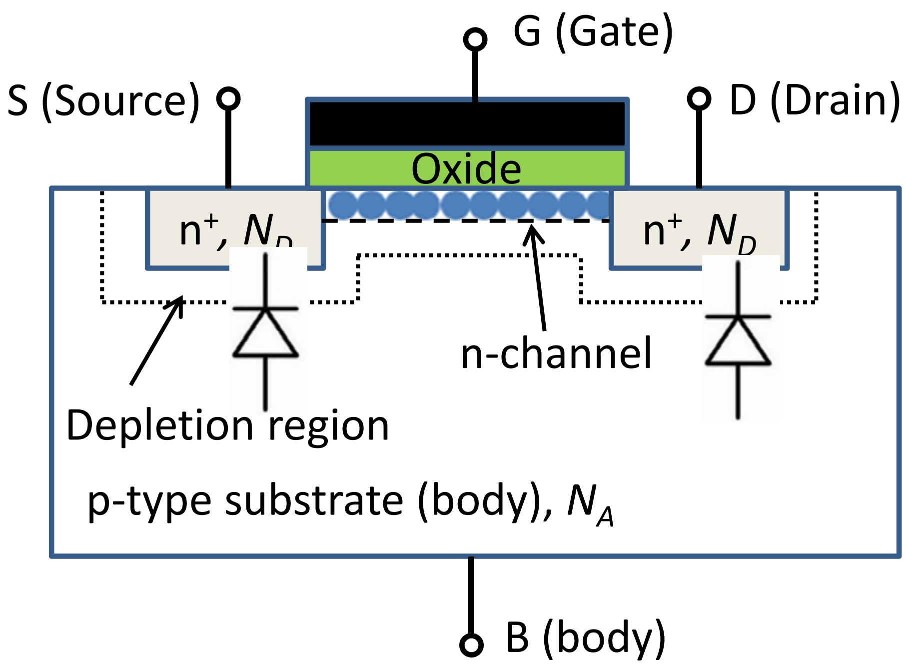
p-type semiconductor substrate (as in n-channel MOSFET)

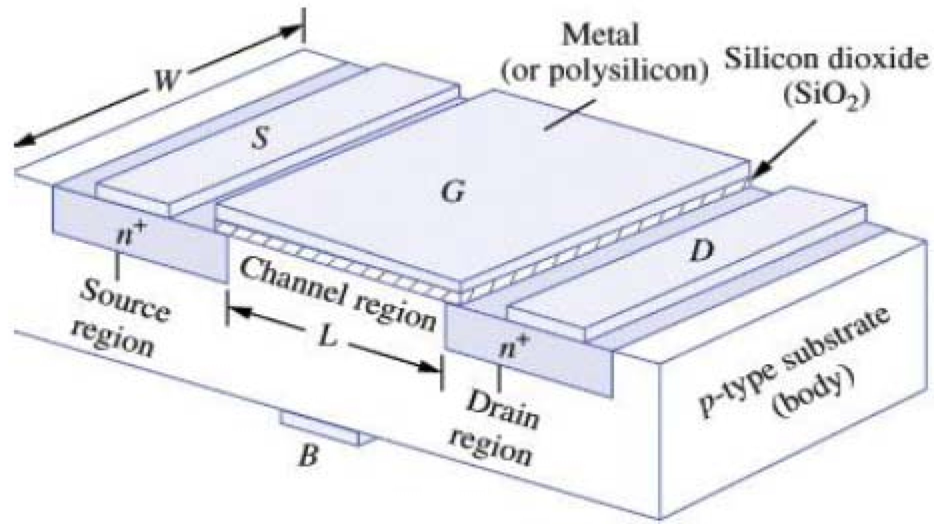


n-type semiconductor substrate (as in p-channel MOSFET)



n-MOSFET

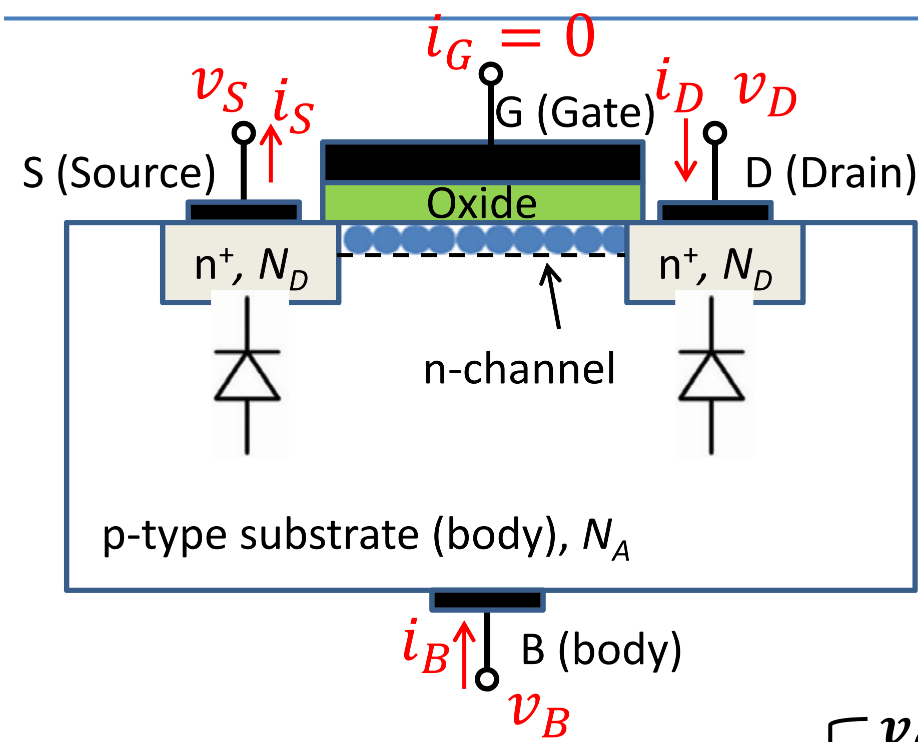




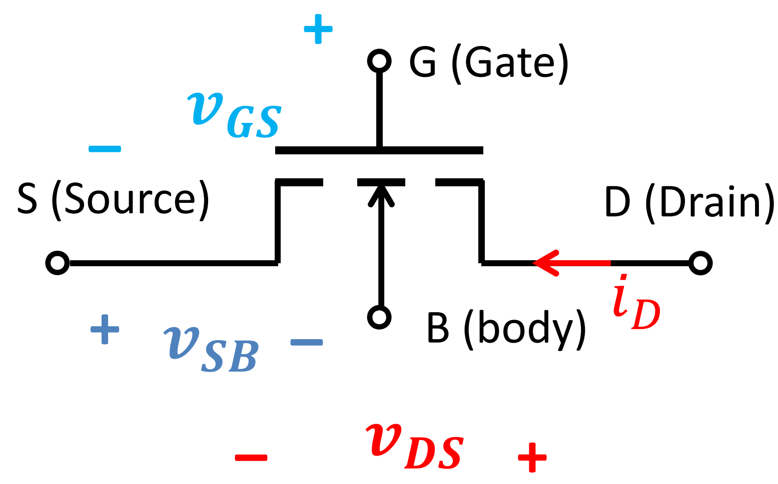
When $V_G > V_T$, an n-channel is formed between source (D) and drain (S).

4 device terminals:
Gate(G), Drain(D), Source(S) and Body(B).
Source and drain regions form *p-n* junctions with substrate ($V_{SB} \geq 0$)

n-MOSFET



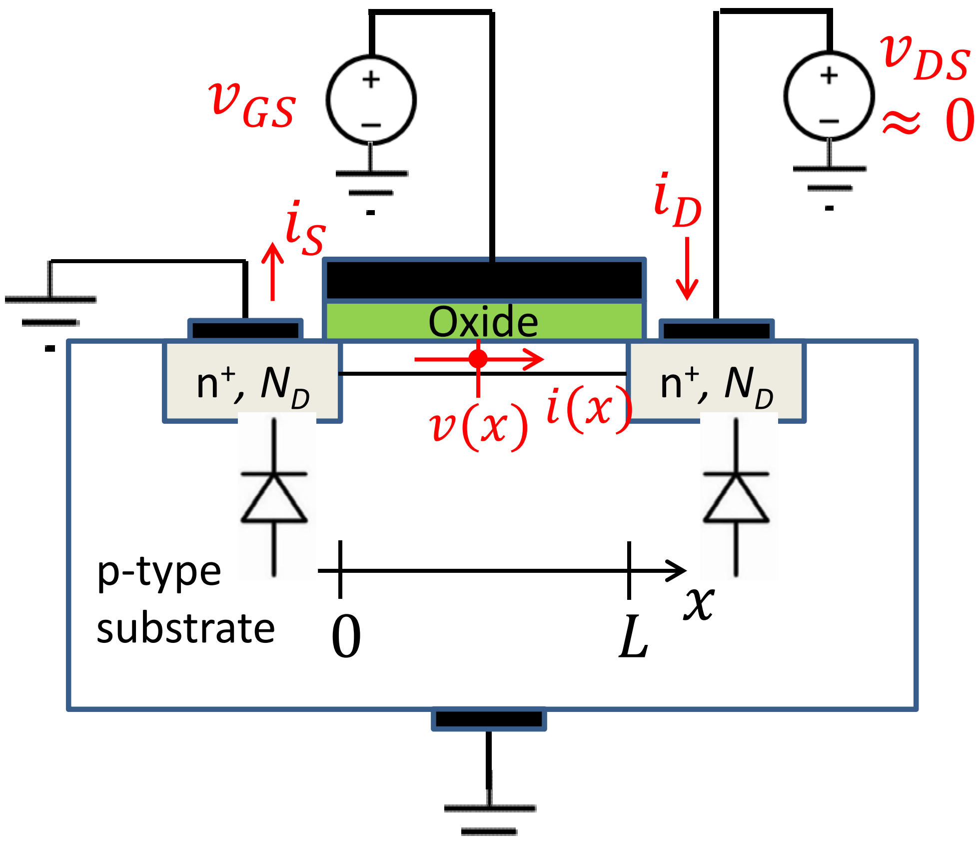
$i_G, i_B \approx 0 \Rightarrow i_D = i_S$



Device state: (v_{GS}, v_{DS}, v_{SB})
- v_{GS}: Transfer characteristics
- v_{DS}: Output characteristics
- v_{SB}: body-effect (higher order effect)

Want to describe: $i_D = f(v_{GS}, v_{DS}, v_{SB})$

n-MOSFET Analysis (Triode)



$v(0) = 0, v(L) = v_{DS}$

- Goal: Find $i_D = f(v_{GS}, v_{DS})$ when v_{DS} is small and $v_{SB} = 0$
- Inversion charge per area at any point in the channel:

$$Q'' = -C''_{\text{ox}}(v_{GC} - V_{TN}) = -C''_{\text{ox}}(v_{GS} - v(x) - V_{TN}) \quad ①$$

- Current in the channel:

$$i(x) = WQ''(x)(-\mu_n E_x) \quad ②$$

- Electric field:

$$E_x = -\frac{dv(x)}{dx} \quad ③$$

n-MOSFET Analysis (Triode)

- Combining ①②③:

$$i(x) = -\mu_n C''_{\text{ox}} W (v_{GS} - v(x) - V_{TN}) \frac{dv(x)}{dx}$$

- Integrate between 0 and *L*: $v(0) = 0, v(L) = v_{DS}$

$$\int_0^L i(x)dx = \int_0^{v_{DS}} -\mu_n C''_{\text{ox}} W (v_{GS} - v(x) - V_{TN}) dv(x)$$

- Current must be equal in the channel: $i(x) = -i_D$ Notice the sign!
- We get the triode region formula:

$$i_D = K'_n \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$$ where $K'_n = \mu_n C''_{\text{ox}}$.

- The channel exists as long as $v_{GC} = v_{GS} - v(x) > V_{TN}$ for all $0 < x < L$. This requires $v_{GS} \geq v(x)_{\max} + V_{TN} = v_{DS} + V_{TN}$
- Thus the condition for triode region operation is: $v_{GS} - v_{DS} \geq V_{TN}$

Important Parameters

- K_n': Process transconductance parameter
  - $K_n' = \mu_n C''_{\mathrm{ox}}$ [A/V^2] (fixed for a given technology)
- K_n : Device transconductance parameter
  - $K_n = K_n' \frac{W}{L}$ [A/V^2] (related to device dimensions)
- μ_n: electron mobility in the channel [cm^2/V-s], generally lower than in bulk (surface scattering).
- C''_{ox} : oxide capacitance per unit area [F/cm^2]
  - $C''_{\mathrm{ox}} = \epsilon_{\mathrm{ox}}/T_{\mathrm{ox}}$
  - ϵ_{ox}: oxide permittivity [F/cm]
  - $\epsilon_{\mathrm{ox}} = \epsilon_r \epsilon_0 = 3.9\epsilon_0$ (ϵ_r = 11.7 for Si, 3.9 for SiO_2)
  - T_{ox}: oxide thickness [cm]

Triode Region I-V Characteristics

$$i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$$

- When v_{DS} is small, ignore 2nd order terms

$$i_D = K_n' \frac{W}{L}(v_{GS} - V_{TN}) v_{DS}$$

- i_D proportional to v_{DS} => the MOSFET is like a resistor (resistor value controlled by v_{GS})
- On-resistance:

$$R_{\text{on}} = \left(\frac{\partial i_D}{\partial v_{DS}}\right)^{-1} = \frac{1}{K_n' \frac{W}{L}(v_{GS} - V_{TN} - v_{DS})}$$