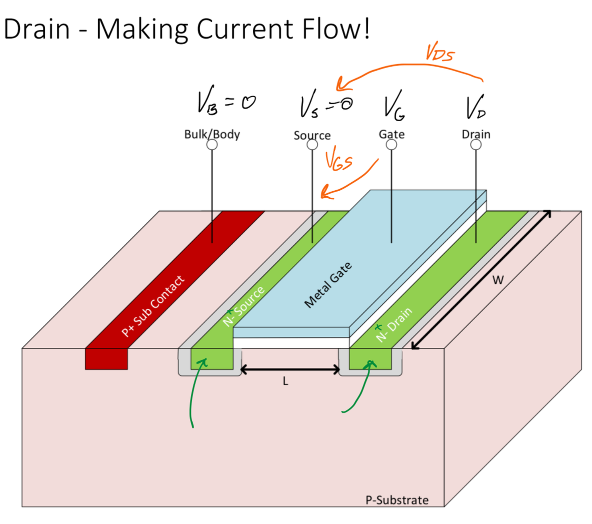
MOSFETs Part 10: Adding Source & Drain - Making Current Flow!

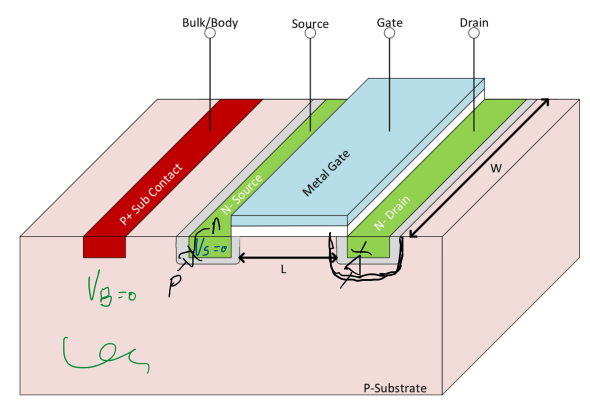
Thursday 19 March 2020 13:51

- MOSFET Formed by placing n+ Source and Drain ~~Depletions~~ Diffusions on either side of the gate
- Note Bulk/Body contact on the top for ease of manufacture
  - No Different to previous analysis
- Contacts are typically assumed to be biased:
  - Bulk: $V_B = 0$
  - Source: $V_S = 0$
  - Gate: $V_G = \text{Variable} = V_{GS}$
  - Drain: $V_D = \text{Variable} = V_{DS}$ (Real Names)



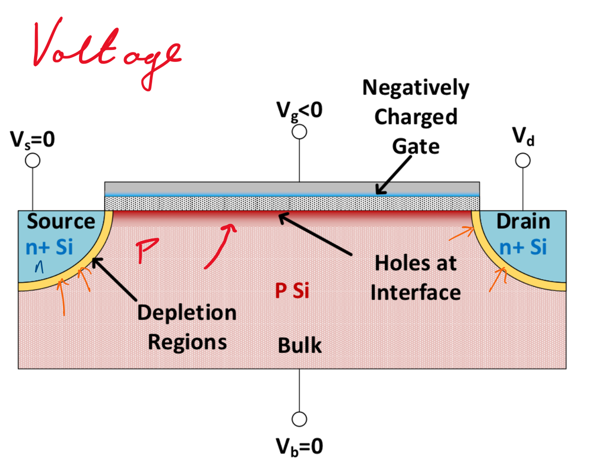
Zero Gate Voltage

- Let: $V_G = 0$ (or Commonly $V_{GS} = 0$)
- Bulk is p-type and Source is n+-type
  - $V_B = V_S = 0$
  - Depletion Region around source from unbiased P-N Junction
- Bulk is p-type and Drain is n+-type
  - $V_B = 0$, $V_D > 0$
  - Large Depletion region around Drain from reverse Biased P-N Junction
- No Current can flow!
- Channel is either in accumulation or depletion



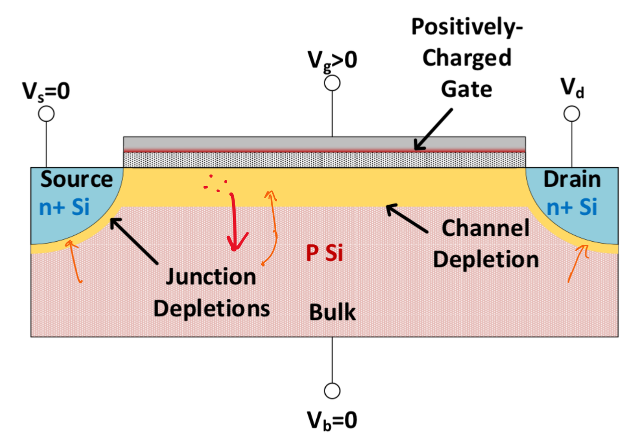
Negative Gate Voltage

- Let: $V_G < 0$
- Channel Region enters Accumulation
- Majority Carriers accumulate at the interface
- Depletion Region remains around Drain & Source
- No Current can Flow!



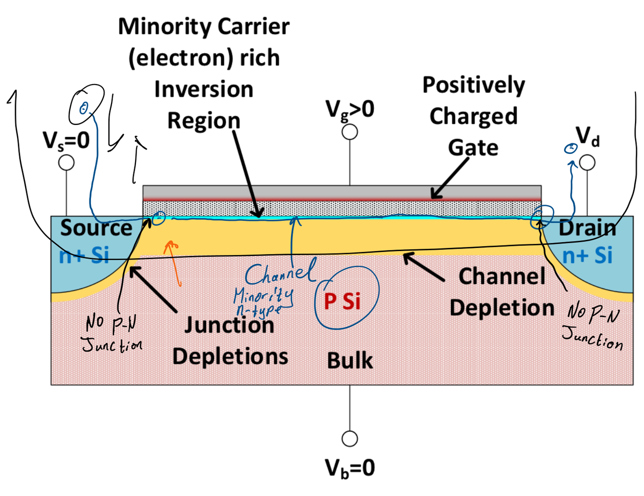
Small Positive Gate Voltage

- Let: $V_G > 0$, Small
- Majority Carriers pushed out of interface
- Interface enters Depletion
- Depletion region continuous between source & drain
- No current Can flow



Large Positive Gate Bias = Inversion

- Let: $V_G >> 0$
- Interface enters Strong Inversion
- Minority Carriers form Channel
- Channel is effectively n-type
  - No P-N Junction between Source & Channel
  - No P-N Junction between Drain & Channel
- **Current can flow between Source and Drain!**



Current in the MOSFET: Setup

- Place a Voltage on the Drain V_D
  - Now a Potential difference between Drain and Source V_{DS}
- As a result, A current will flow between Drain & Source
- We define the horizontal as the *y* axis with the following quantities:

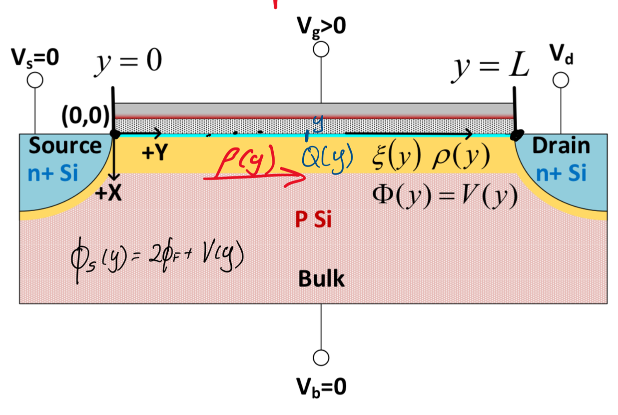
$V(y) \leftarrow$ Horizontal Component of the Channel Voltage

$\phi_s(y) \leftarrow$ Surface Potential as a function of y

$\mathcal{E}(y) \leftarrow$ E. field

$\rho(y) \leftarrow$ Chg. density

$Q(y) \leftarrow$ total Charge in a given Slice @ y



- We define the Drain and Source Voltages:

$$V(y=0) = 0$$
$$V(y=L) = V_D$$

- Remember that Electric Field is just the rate of change of potential:

$$\mathcal{E}(y) = -\frac{dV(y)}{dy}$$

- Uniform Carrier Concentration in the channel --> Current is dominated by **Drift Current**:

Current Density $\rightarrow J = \sigma \mathcal{E}$ ($\mathcal{E}$: E field; σ: Conductivity $-q\mu n$; Q?)

- Conductivity depends on charge in the channel!
  - This is why we went to so much effort to find channel charge!

$$\sigma = -q\mu_n n$$

But: $Q = -qn$

So: $\sigma = Q\mu_n$

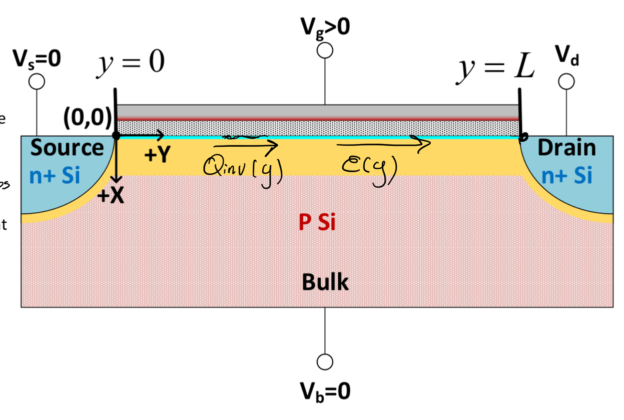
$$J = Q\mu_n \mathcal{E}(y)$$

Current in the MOSFET: Current Density

- In the Context of the MOSFET, The Current Density is given by:

$$J(y) = Q_{inv}(y)\mu_n \mathcal{E}(y)$$

- The Inversion Charge Q_{inv} may not be constant along the channel due to Drain Voltages (shown later)
- The Electric Field $\mathcal{E}(y)$ is due to Drain-Source Voltage V_{DS}
- Once we know Current Density, We can find total current in the MOSFET...

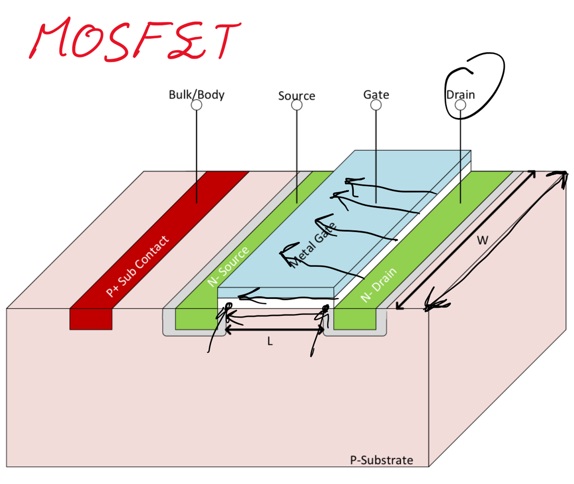


Current in the MOSFET

- Current Density is Current per unit Width:

$$J = \frac{-I}{W}$$

$$I = -J \times W$$



- So the total Drain Current is given by:

$$I_D = -WJ(y)$$
$$I_D = -W\mu_n Q_{inv}(y)\mathcal{E}(y)$$
$$I_D = -W\mu_n Q_{inv}(y)\frac{dV(y)}{dy}$$

- But what is $Q_{inv}(y)$?

Inversion Charge Along y

- We know total charge at the gate:

$$Q = -(Q_{dep}(y) + Q_{inv}(y)) \Rightarrow Q_{inv} = -Q_G - Q_{dep}$$

- Depletion Charge is given by:

$$Q_{dep} = -\sqrt{2q\varepsilon_{Si}N_A\phi_s(y)}$$

- Charge Equation gives us total Gate Charge:

$$Q_G = C_{ox}[V_G - \phi_s(y)]$$

- Substituting these to find Q_{inv}:

$$Q_{inv}(y) = -\left(C_{ox}[V_G - \phi_s(y)] - \sqrt{2q\varepsilon_{Si}N_A\phi_s(y)}\right)$$

- We should now be able to solve for Drain Current:

$$I_D = -W\mu_n Q_{inv}(y)\frac{dV(y)}{dy}$$

$$I_D\,dy = -W\mu_n Q_{inv}(y)\,dV(y)$$

- In order to remove the derivative (d) terms, we must integrate both sides:

$$\int_0^L I_D\,dy = \int_{V_S=0}^{V_D} -W\mu_n Q_{inv}(y)\,dV(y) \qquad \gamma = \frac{\sqrt{2q\varepsilon_{Si}N_A}}{C_{ox}}$$

- This integration is very involved. The solution is given:

$$I_D = \frac{W}{L}\mu_n C_{ox}\left([V_G - 2\phi_F - \frac{V_{DS}}{2}]V_{DS} - \frac{2}{3}\gamma(2\phi_F + V_{DS})^{3/2}\right) \qquad V_{TO}?$$

- This solution is pretty complicated, but can be approximated by:

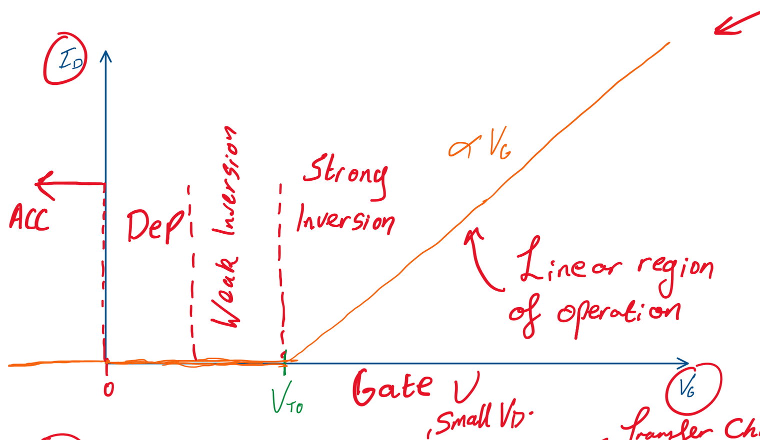
$$** \quad I_D \simeq \frac{W}{L}\mu_n C_{ox}\left([V_G - V_{TO}]V_{DS} - \frac{1}{2}V_{DS}^2\right) \quad **$$

(Linear W/ V_G; Quadratic W/ V_D)

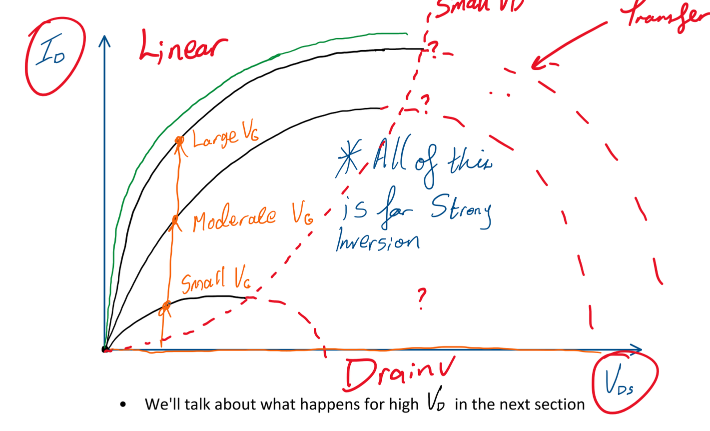
$$V_{TO} = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F}$$

- Let's think about what this means for a minute:

Transfer function



Transfer Characteristic



- We'll talk about what happens for high V_D in the next section

$$V_{ox} = \frac{Q_{ox}}{C_{ox}} = \frac{Q_{inv}}{C_{ox}}$$

$$Q_G = Q_{ox} + Q_{dep} \qquad Q_G = C_{ox}[V_G - \phi_s(y)]$$
$$Q_G = -(Q_{inv} + Q_{dep})$$

$$Q_{inv} = -Q_G - Q_{dep}$$
$$Q_{inv} = -\left(C_{ox}[V_G - \phi_s(y)] - \sqrt{2q\varepsilon_{Si}N_A\phi_s(y)}\right)$$

$$L I_D = -W\mu_n \int_{V_S}^{V_D} Q_{inv}(y)\,dV(y)$$

$$W\mu_n \int_{V_S}^{V_D} C_{ox}[V_G - (2\phi_F + V(y))] - \sqrt{2q\varepsilon_{Si}N_A[2\phi_F + V(y)]}\,dV(y)$$

Substitute $u = 2\phi_F + V(y)$

$$= W\mu_n \int_{V_S}^{V_D} C_{ox}[V_G - 2\phi_F - V(y)]\,dV(y) - \int_{V_S}^{V_D}\sqrt{2q\varepsilon_{Si}N_A}\sqrt{2\phi_F + V(y)}\,dV(y)$$

$$= W\mu_n \left\{C_{ox}[V(y)(V_G - 2\phi_F) - \tfrac{1}{2}V(y)^2]\right\}_{V_S}^{V_D} - \sqrt{2q\varepsilon_{Si}N_A}\left\{\tfrac{2}{3}(2\phi_F + V(y))^{3/2}\right\}_{V_S}^{V_D}$$

$$= W\mu_n \left(C_{ox}[V_{DS}(V_G - 2\phi_F) - \tfrac{V_{DS}^2}{2}] - \tfrac{2}{3}\sqrt{2q\varepsilon_{Si}N_A}\left[(2\phi_F + V_D)^{3/2} - (2\phi_F + V_S)^{3/2}\right]\right)$$

Let $\gamma = \frac{\sqrt{2q\varepsilon_{Si}N_A}}{C_{ox}}$

$V_S = 0$

$$= W\mu_n C_{ox}\left([V_G - 2\phi_F - \tfrac{V_{DS}}{2}]V_{DS} - \tfrac{2}{3}\gamma[(2\phi_F + V_D)^{3/2} - (2\phi_F + V_S)^{3/2}]\right)$$

$$= W\mu_n C_{ox}\left([V_G - 2\phi_F - \tfrac{V_{DS}}{2}]V_{DS} - \tfrac{2}{3}\gamma(2\phi_F + V_{DS})^{3/2}\right) \qquad (\tfrac{1}{2}V_{DS}^2)$$

Simplification:

$$I_D = \frac{W}{L}\mu C_{ox}\left(\tfrac{1}{2}V_{DS}^2 + V_G V_{DS} - 2\phi_F V_{DS} - \tfrac{2}{3}\gamma(2\phi_F + V_{DS})^{3/2}\right)$$

$$\tfrac{2}{3}\gamma\sqrt{(2\phi_F + V_{DS})^3}$$
$$\tfrac{2}{3}\gamma\sqrt{(2\phi_F + V_{DS})(4\phi_F^2 + 4\phi_F V_{DS} + V_{DS}^2)}$$
$$\tfrac{2}{3}\gamma\sqrt{(8\phi_F^3 + 8\phi_F^2 V_{DS} + 2\phi_F V_{DS}^2 + 4\phi_F^2 V_{DS} + 4\phi_F V_{DS}^2 + V_{DS}^3)}$$
$$\tfrac{2}{3}\gamma\sqrt{(8\phi_F^3 + 12\phi_F^2 V_{DS} + 6\phi_F V_{DS}^2 + V_{DS}^3)}$$

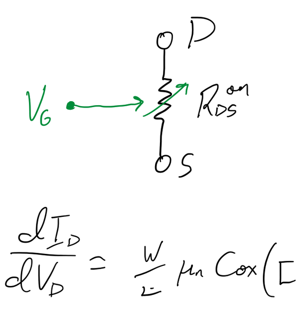
Small V_{DS}:

$$\tfrac{2}{3}\gamma\sqrt{8\phi_F^3}$$

$$V_{TO} = V_{FB} + 2\phi_F + \frac{\sqrt{4q\varepsilon_{Si}N_A\phi_F}}{C_{ox}}$$
$$= V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F}$$

Small Signal Model

- This is called the **Linear Region** since drain current is linear with V_G
- The drain current is quadratic with respect to V_D however.
- We assume that the drain voltage is small, and model the device as a gate-controlled Resistor:



$$\frac{1}{R_{DSon}} = \frac{dI_D}{dV_D} = \frac{W}{L}\mu_n C_{ox}([V_G - V_{TO}] - V_D) \simeq \frac{W}{L}\mu_n C_{ox}(V_G - V_{TO})$$

(Small: V_D)