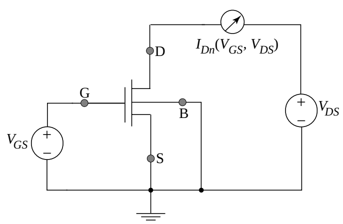
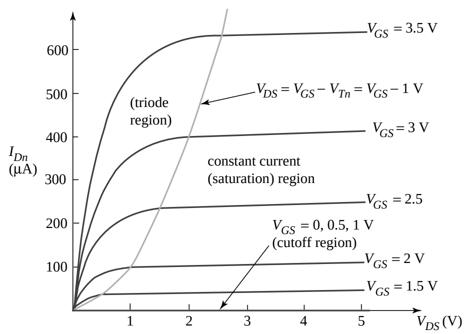
# n-Channel MOSFET Drain Characteristics

Set-up: $I_G = 0$, $V_{DB} = V_{DS} > 0$ to reverse-bias pn junctions to bulk.

- Measurement scheme: short bulk to source to make it a three terminal device, vary gate voltage, drain voltage and see effect on drain current.




(a)

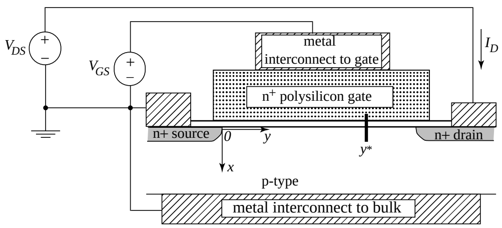



(b)

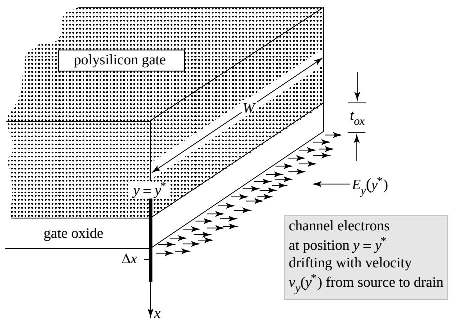


# MOSFET in Action

- Close-up of drifting electrons in the channel between source and drain.




(a)




(b)

# Drift Current Equation

- Drift current for electrons in the channel:

$$J_y(x, y) = -qn(x, y)v_y(y)$$

The drain current at position $y$ is the integral of the drift current density across the cross section. Since the conventional direction of $I_D$ is *opposite* to the direction of the $y$ axis, we insert a minus sign:

$$I_D = -W\int_0^{\Delta x} J_y(x, y)dx = Wv_y(y)\left(\int_0^{\Delta x} qn(x, y)dx\right)$$

- The integral is the negative of the electron charge in the channel, per unit area, at point $y$. The symbol for this quantity is - $Q_N(y)$:

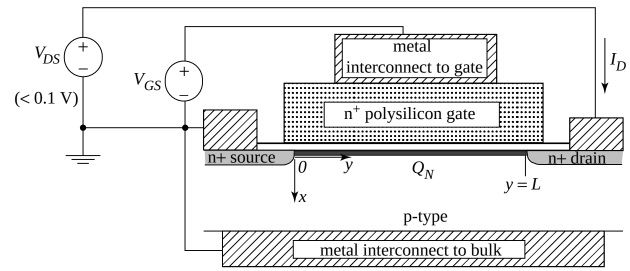
$$\boxed{I_D = -Wv_y(y)Q_N(y)}$$

Note that $I_D$ isn't a function of the position in the channel



# MOSFET as a Circuit Element

- Start simple -- small $V_{DS}$ makes the channel uniform




- Channel charge: MOS capacitor in inversion, with $V_{GB} = V_{GS}$.

$$Q_N = -C_{ox}(V_{GB} - V_{Tn}) = -C_{ox}(V_{GS} - V_{Tn})$$

- Drift velocity: electric field is just $E_y = -V_{DS} / L$ so $v_y = -\mu_n(-V_{DS} / L)$

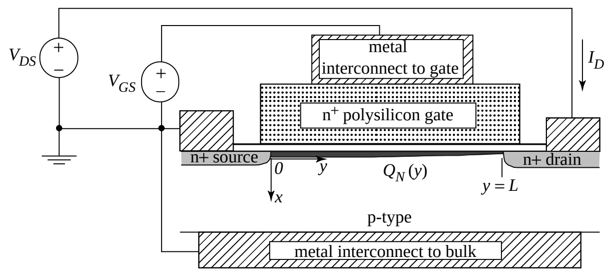
- Drain current equation for $V_{DS}$ "small" ... say, less than 0.1 V.

$$I_D = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})V_{DS}$$

Note that $I_D$ is proportional to $V_{DS}$ with channel resistance under gate control. This voltage controlled resistor region is sometimes useful.

# Triode Region

- Increase $V_{DS}$ -- channel charge becomes a function of position $y$.




- First try: approximate the drain current equation by taking averages of the channel charge and the drift velocity

$$I_D \approx -W\overline{Q_N}\overline{v_y}$$

- Average drift velocity: still use $\mu_n (V_{DS} / L)$ -- which is a very rough approximation.



# Triode Region (Cont.)

- Next, approximate the average channel charge by averaging $Q_N(y=0)$ at the source end and $Q_N(y=L)$ at the drain end of the channel:

$$Q_N(y=0) = -C_{ox}(V_{GS} - V_{Tn})$$

At the drain end, the positive drain voltage *reduces* the magnitude of the channel charge ... why? The effect can be approximated by using $V_{GD}$ (the drop from drain to channel, at $y = L$) --

$$Q_N(y=L) = -C_{ox}(V_{GD} - V_{Tn}) = -C_{ox}(V_{GS} - V_{DS} - V_{Tn})$$

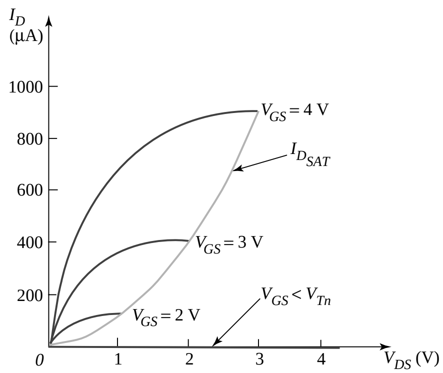
Note that $V_{GD} = V_{GS} - V_{DS} > V_{Tn}$ in order for there to be a channel left at the drain end.

- Substituting, we derive the equation for the triode region, which is defined by $V_{GS} - V_{DS} > V_{Tn}$ and $V_{GS} > V_{Tn}$.

$$I_D = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn} - V_{DS}/2)V_{DS}$$

# Drain Characteristics

- Example: $\mu_n C_{ox} (W/L) = 50\ \mu A/V^2$, $V_{Tn} = 1$ V, and $(W/L) = 4$.




- What happens when $V_{DS} > V_{GS} - V_{Tn} = V_{DS(sat)}$ ? $|Q_N(y = L)| = 0$!

  Initial thought is that the lack of a channel at the drain end means that $I_D$ must drop to zero ... WRONG!

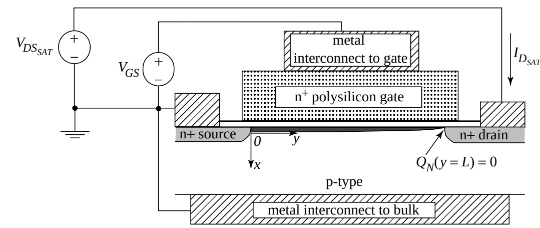
  Drain current "saturates" (stops changing) and remains constant (to a first approximation) at the value given by $V_{DS} = V_{DS(sat)}$ .



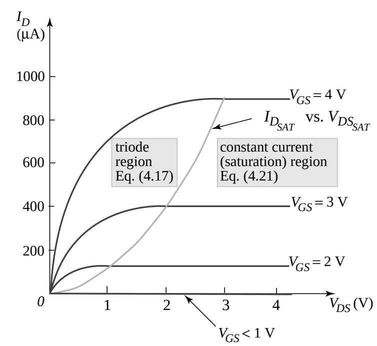
# Saturation Region

- When $V_{GS} > V_{Tn}$ and $V_{DS} > V_{DS(sat)} = V_{GS} - V_T$, the drain current is:

$$I_D = I_{D(sat)} = \mu_n C_{ox}\left(\frac{W}{2L}\right)(V_{GS} - V_{Tn})^2$$




- Full model:



# MOSFET Circuit Models

- n-channel MOSFET drain current in cutoff, triode, and saturation:

$$I_D = 0\text{ A} \qquad (V_{GS} \le V_{Tn})$$

$$I_D = \mu_n C_{ox}(W/L)[V_{GS} - V_{Tn} - (V_{DS}/2)](1 + \lambda_n V_{DS})V_{DS} \qquad (V_{GS} \ge V_{Tn},\ V_{DS} \le V_{GS} - V_{Tn})$$

$$I_D = \mu_n C_{ox}(W/(2L))(V_{GS} - V_{Tn})^2(1 + \lambda_n V_{DS}) \qquad (V_{GS} \ge V_{Tn},\ V_{DS} \ge V_{GS} - V_{Tn})$$

Numerical values:

$\mu_n$ is a function of $V_{GS}$ along the channel and is much less than the mobility in the bulk (typical value 215 $\text{cm}^2/(\text{Vs})$ ) -- therefore, we consider that $\mu_n C_{ox}$ is a measured parameter. Typical value: $\mu_n C_{ox} = 50\ \mu\text{AV}^{-2}$

$\lambda_n$, sometimes called the channel length modulation parameter, increases as the channel length $L$ is reduced:

$$\lambda_n \approx \frac{0.1\mu\text{mV}^{-1}}{L}$$

The triode region $I_D$ equation has $(1 + \lambda_n V_{DS})$ added in order to avoid a jump at the boundary with the saturation region. For hand calculation of DC voltages and currents, this term is usually omitted from $I_D$.

$V_{Tn}$ = threshold voltage = 0.7 - 1.0 V typically for an n-channel MOSFET.