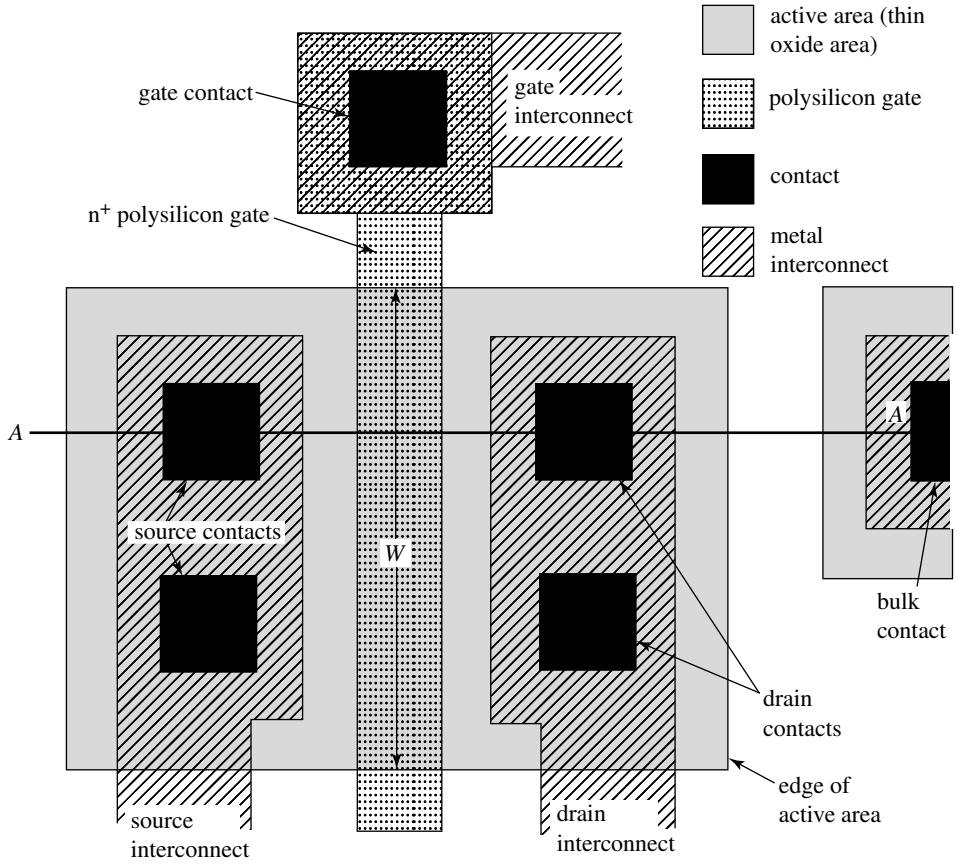
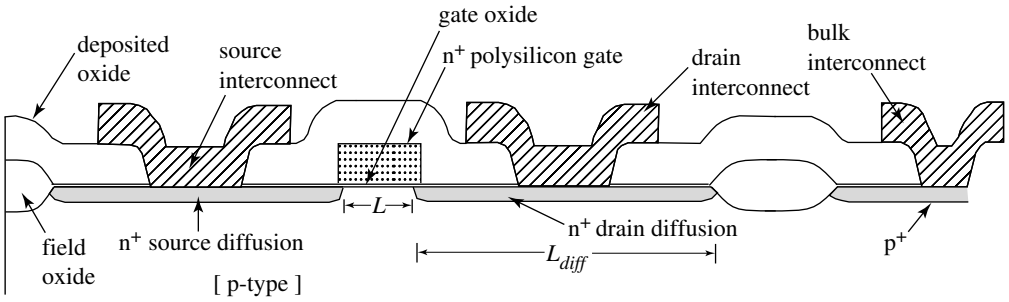
I. MOS Field Effect Transistors

A. Crossection and Layout

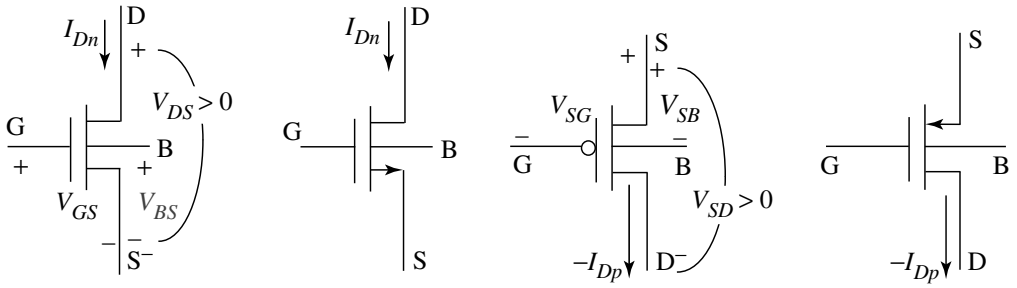


(a)

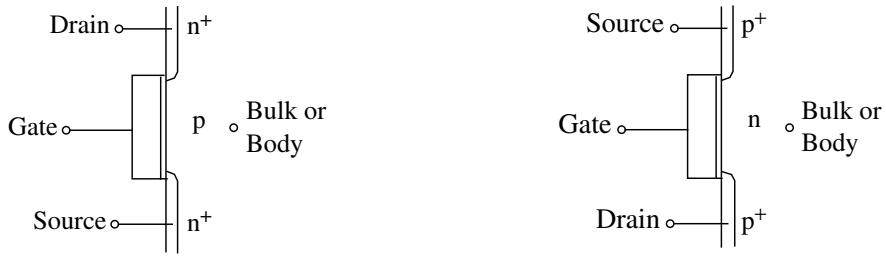


B. MOSFET Circuit Symbols

- Two complementary devices: both are very useful
- p-substrate (n-type channel under gate oxide) - NMOS
- n-substrate (p-type channel under gate oxide) - PMOS



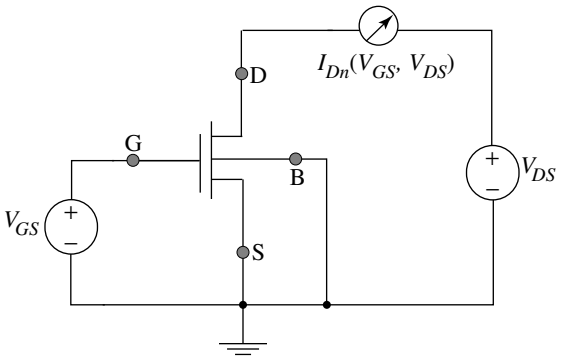
(a) n-channel MOSFET (b) p-channel MOSFET



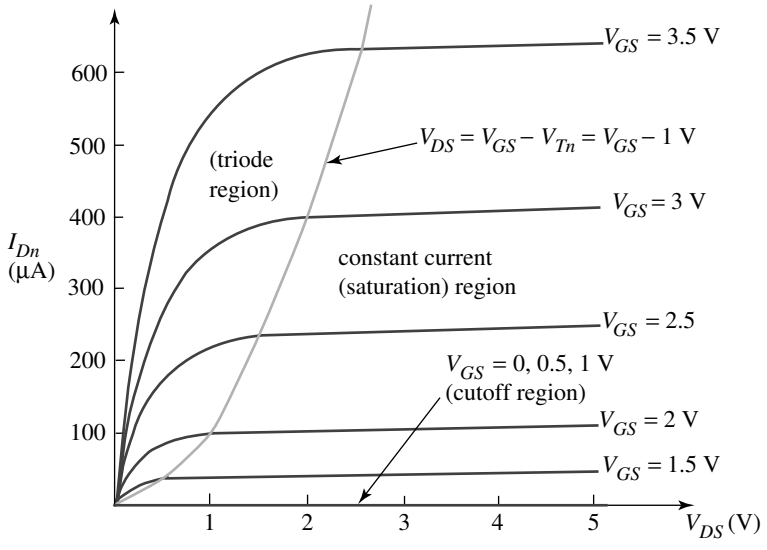
- *Four* electrical terminals: source (lowest potential for n-channel, highest for p-channel), drain, gate, and bulk.
- Basic concept: inversion layer (called the channel) formed under gate between source and drain enables drift current
- Channel carriers are supplied by the source and drifted to the drain

C. MOSFET Drain Characteristics

- Observations: $I_G = 0$, V_{DB}, $V_{SB} \geq 0$ to reverse-bias, drain-bulk source-bulk junctions.
- Measurement scheme: short bulk to source to make it a three terminal device, sweep drain voltage for various gate voltages. Measure drain current.



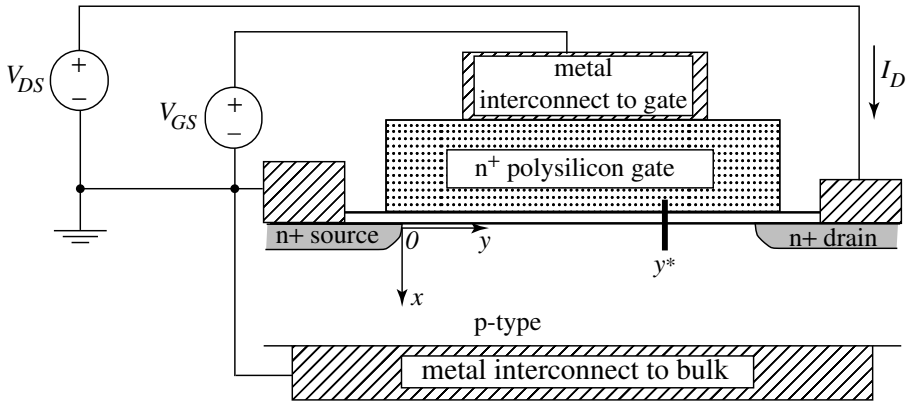
(a)



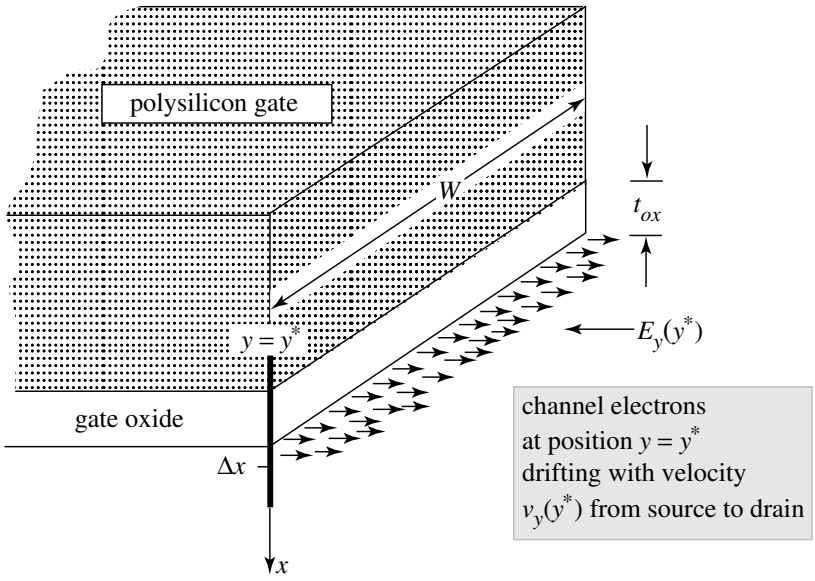
(b)

II. Quantitative MOSFET-NMOS

A. Geometry



(a)



(b)

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 add a minus sign):

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

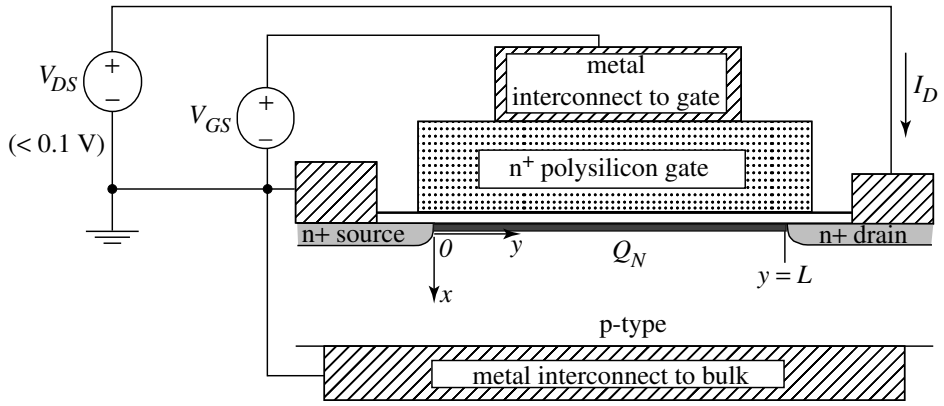
- The integral is the magnitude of the electron charge in the channel, per unit area. The symbol for this quantity is $Q_N(y)$:

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

- I_D is not a function of the position in the channel

C. MOSFET DC Model: a First Pass

- Assume small V_{DS} - makes the channel uniform along y



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

$$Q_N = -C_{ox}(V_{GB} - V_{Tn}) = -C_{ox}(V_{GS} - V_{Tn}) \; for \; (V_{GS} \geq V_{Tn})$$

$$Q_N = 0 \; for \; (V_{GS} < V_{Tn})$$

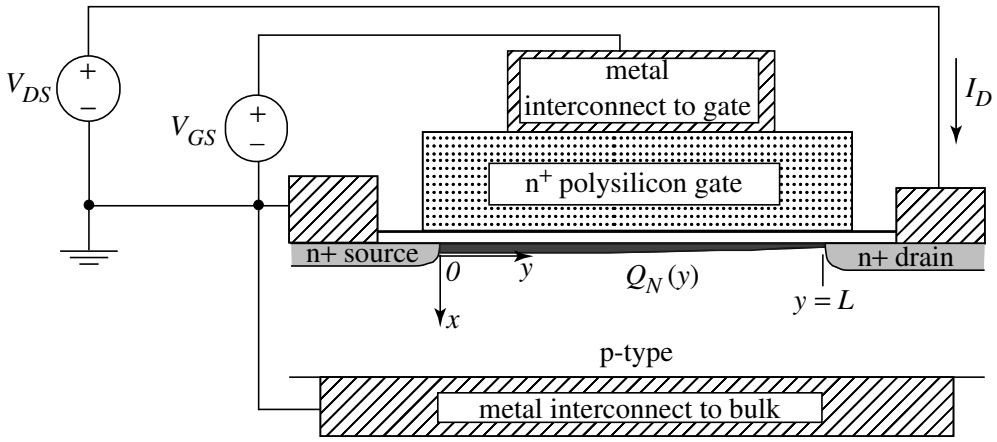
- Drift velocity: electric $E_y = -V_{DS}/L$. .. $v_y = \mu_n V_{DS}/L$
- Drain current equation for V_{DS} "small" ... < 0.1 V.

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

- Conclude that I_D is proportional to V_{DS} with channel resistance under gate voltage control.

D. Triode Region

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



- First pass: 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.

$$\overline{v_y} \approx \mu_n \frac{V_{DS}}{L}$$

D. Triode Region (Cont.)

- 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
- Source End

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

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

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

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

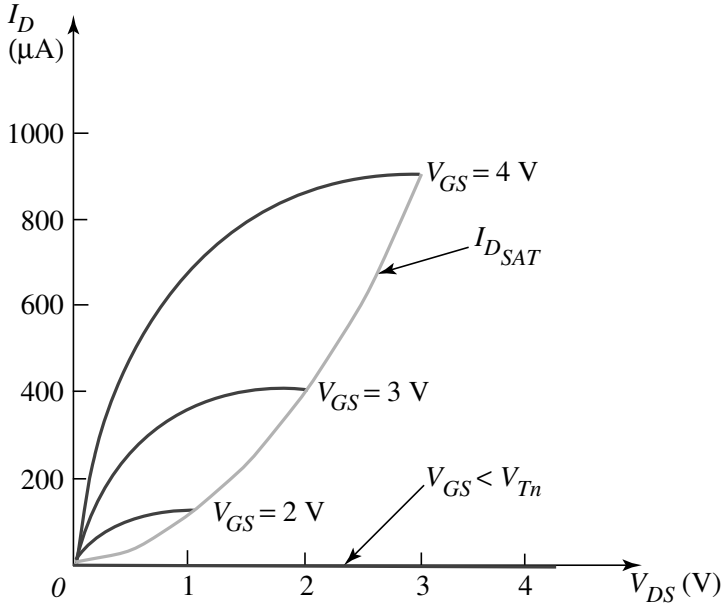
$$Q_N = -C_{OX}(V_{GS} - V_{Tn} - V_{DS}/2)$$

- Substituting—

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

III. Drain Current Characteristics

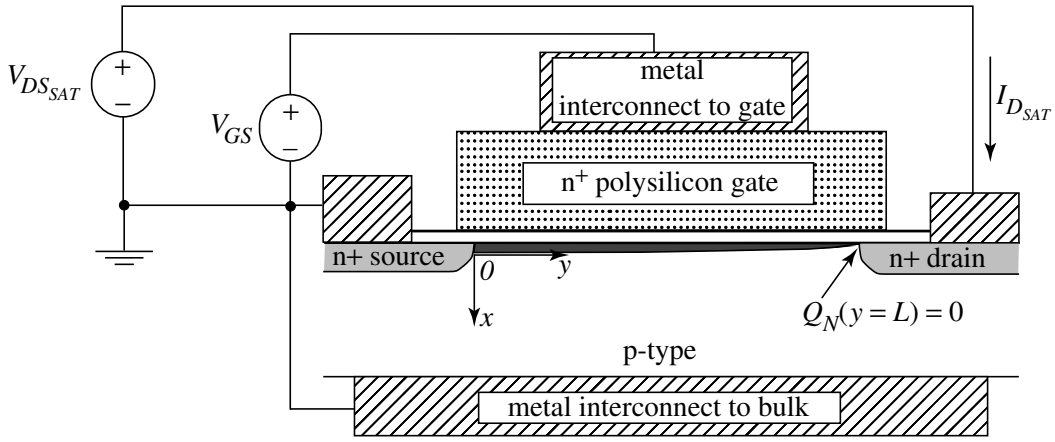
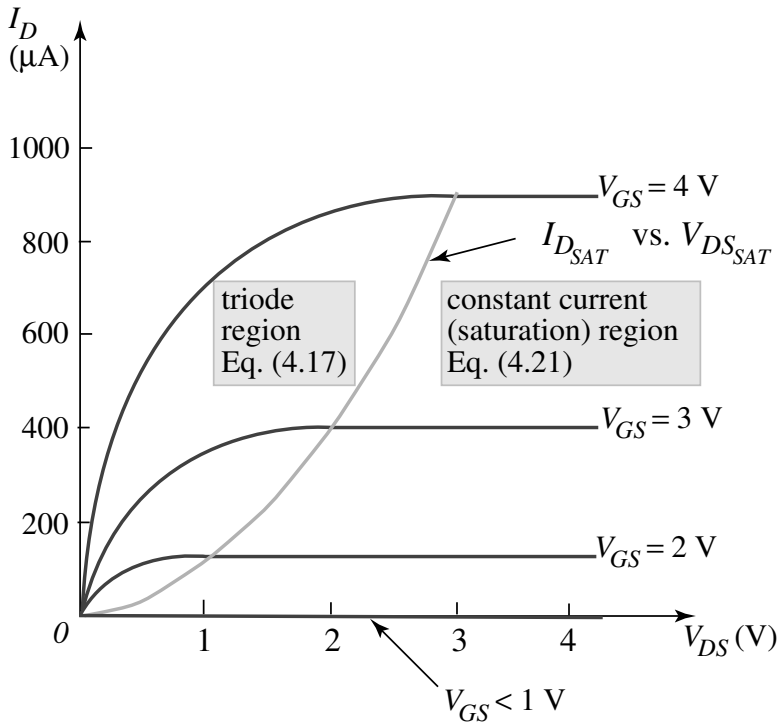
A. Triode Region Example:



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

B. Saturation

- When $V_{DS} > V_{GS} - V_{Tn}$ ... $Q_N(y = L) = 0$ $\qquad V_{GD} < V_{Tn}$
- Drain terminal loses control over channel
- Drain current "saturates" and remains constant (to first approximation) at the value given by $V_{DS(sat)}$.
- When $V_{GS} > V_{Tn}$ and $V_{DS} > V_{DS(sat)} = V_{GS} - V_{Tn}$, the drain current is:

$$I_D = I_{D(sat)} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})^2$$

B. Saturation (con't)