MOSFET Terminals

- The voltage applied to the GATE terminal determines whether current can flow between the SOURCE & DRAIN terminals.
  - For an n-channel MOSFET, the SOURCE is biased at a *lower* potential (often 0 V) than the DRAIN

    (Electrons flow from SOURCE to DRAIN when $V_G > V_{t0}$)
  - For a p-channel MOSFET, the SOURCE is biased at a *higher* potential (often the supply voltage V_{DD}) than the DRAIN

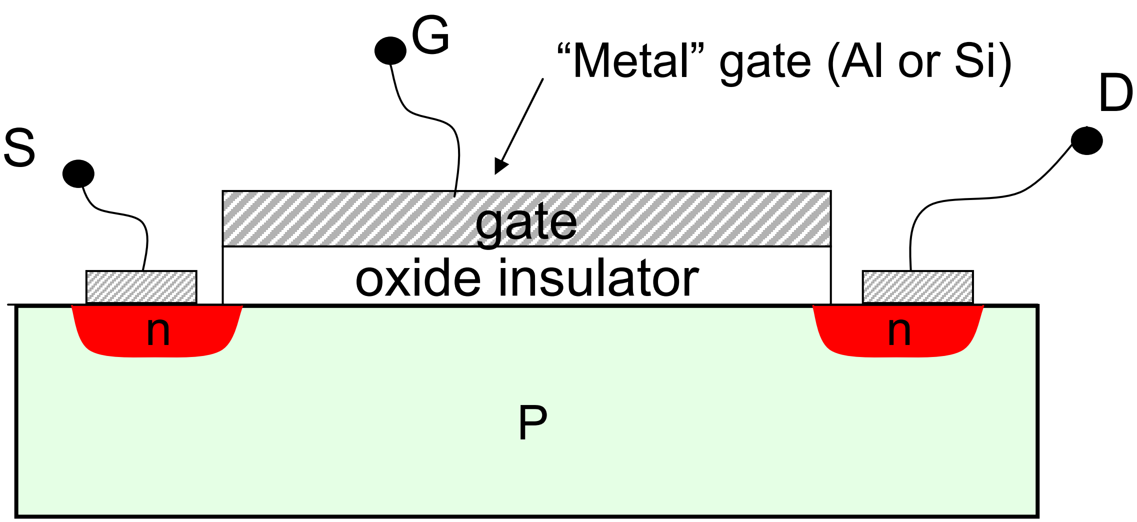
    (Holes flow from SOURCE to DRAIN when $V_G < V_{t0}$)

- The BODY terminal is usually connected to a fixed potential.
  - For an n-channel MOSFET, the BODY is connected to 0 V
  - For a p-channel MOSFET, the BODY is connected to V_{DD}

MOSFET Structure

DEVICE IN CROSS-SECTION

"Metal" "Oxide" "Semiconductor"



- In the absence of gate voltage, no current can flow between S and D.
- Above a certain gate to source voltage V_{t0} (the "threshold"), electrons are induced at the surface beneath the oxide. (Think of it as a capacitor.)
- These electrons can carry current between S and D if a voltage is applied.

MOSFET

- Symbol and subscript convention
  - Upper case for both (e.g. V_D) = DC signal (often as bias)
  - Lower case for both (e.g. v_d) = AC signal (often small signal)
  - Lower symbol and upper sub (e.g. v_D) = total signal = V_D+v_d
- NMOS: Three regions of operation
  - V_{DS} and V_{GS} normally positive values
  - $V_{GS}<V_{t0}$:cut off mode, $I_{DS}=0$ for any V_{DS}
  - $V_{GS}>V_{t0}$:transistor is turned on
    - $V_{DS}< V_{GS}-V_{t0}$: Triode Region $$i_D = K\left[2(v_{GS}-V_t)v_{DS}-v_{DS}{}^2\right]$$
    - $V_{DS}> V_{GS}-V_{t0}$: Saturation Region $$i_D = K\left[\ (v_{GS}-V_t)^2\right]$$
    - Boundary $$v_{GS}-V_t = v_{DS}$$

$$K = \frac{W}{L}\frac{KP}{2}$$

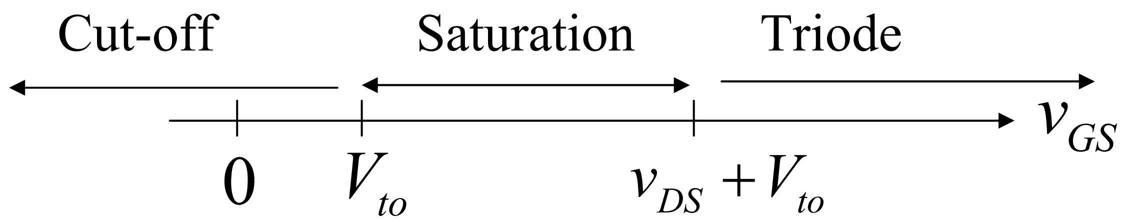
MOSFET

- PMOS: Three regions of operation (interchange > and < from NMOS)
  - V_{DS} and V_{GS} Normally negative values
  - $V_{GS}>V_{t0}$:cut off mode, $I_{DS}=0$ for any V_{DS}
  - $V_{GS}<V_{t0}$:transistor is turned on
    - $V_{DS}> V_{GS}-V_{t0}$: Triode Region $i_D = K\left[2(v_{GS}-V_t)v_{DS}-v_{DS}{}^2\right]$
    - $V_{DS}< V_{GS}-V_{t0}$: Saturation Region $i_D = K\left[\ (v_{GS}-V_t)^2\right]$
    - Boundary $v_{GS}-V_t = v_{DS}$

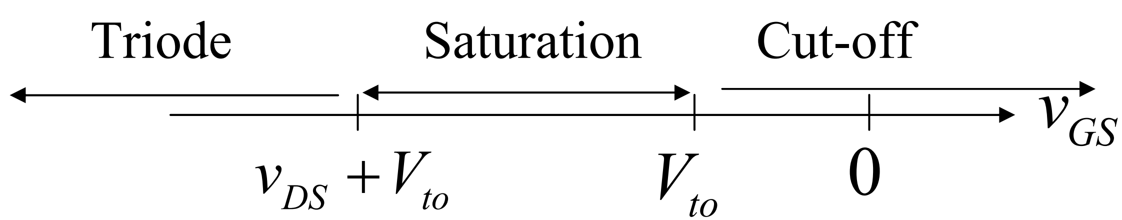
$$K = \frac{W}{L}\frac{KP}{2}$$

MOSFET Operating Regions

NMOS



PMOS



1

We now derive the formulas describing the i_D/v_{DS} characteristic of an n-channel MOSFET in terms of v_{GS}.

Recall from the description of the physics of an n-channel MOSFET in the supplementary notes that there is a threshold voltage V_{t0} such that if $v_{GS} \leq V_{t0}$ then there is no channel for current to flow between the drain and the source. In this case the connection between the drain and the source acts as an open circuit. We have $i_D = 0$ irrespective of the value of v_{DS} (note that we always assume that $v_{DS} \geq 0$, otherwise we would have to interchange the names of drain and source). This is the *cutoff region*.

Next, suppose that $v_{GS} > V_{t_0}$. Now we have a channel of electrons created between the drain and source. If $v_{DS} = 0$, then, of course we have $i_D = 0$ because there is no electric field from the drain to the source in this channel, so there is no drift of electrons. What we want to note, however, is that the charge in this channel, which we measure on a per-unit-area-of-the-gate basis, is proportional to the excess voltage $v_{GS} - V_{t0}$. We write the proportionality constant as C_{ox} since it is a capacitance per unit area, and because the dielectric associated to this corresponding capacitor in a typical MOSFET is silicon dioxide (this separates the metal or polysilicon gate from the base, at whose surface the channel forms). Thus we have the formula

$$Q = -C_{ox}(v_{GS} - V_{t0})$$

for the total charge in the channel per unit area of the gate when $v_{DS} = 0$ and when the applied gate to source voltage v_{GS} exceeds the threshold voltage V_{t0}.

Now suppose that $v_{DS} > 0$ but also $v_{DS} < v_{GS} - V_{t0}$. This is the *triode region.* In this region the channel of electrons exists throughout the length of the MOSFET from the source to the drain. The charge per unit length in the channel decreases linearly as we move from the source to the drain, because the excess voltage across the oxide decreases from $v_{GS} - V_{t_0}$ to $v_{GS} - v_{DS} - V_{t0}$. See Figure 4. We approximate the charge per unit area of the gate in the channel by the average over this linear decrease. This equals

$$\bar{Q} = -C_{ox}(v_{GS} - \frac{v_{DS}}{2} - V_{t0}).$$

Strictly speaking the electric field in the channel is not constant along its length because the channel depth is changing, but we approximate it as constant, equal to $\frac{v_{DS}}{L}$, where L denotes the length of the channel. Let μ_n denote the mobility of electrons. The velocity of the bulk of electrons measured as moving from the source to the drain can then be written as

$$\mu_n \frac{v_{DS}}{L}.$$

The total current flowing from the drain to source can then be written as

$$i_D = W\mu_n \frac{v_{DS}}{L} C_{ox}(v_{GS} - \frac{v_{DS}}{2} - V_{t0}) \qquad (1)$$

where W denotes the width of the gate. We arrive at this formula by approximately figuring out how much charge moves per unit time. The area on the gate corresponding to the amount of charge that moves is got by multiplying the velocity (in the direction from the source to the drain) by the width of the gate; this is then multiplied by the average charge per unit area of the gate that we derived earlier.

Equation (1) is the same as equation (12.2) in the book when one defines KP (using the notation of the book) to be $\mu_n C_{ox}$. Then one would have K (using the notation of the book) equal to $\frac{W}{L}\frac{\mu_n C_{ox}}{2}$ and (1) can be rewritten as

$$i_D = K(2(v_{GS} - V_{t0})v_{DS} - v_{DS}^2)$$

which is equation (12.2) of the book.

Finally, we see that if $v_{GS} > V_{t0}$ and $v_{DS} \geq v_{GS} - V_{t0}$ the channel pinches off near the drain. This is the *saturation region.* The current flowing through then saturates (the electrons make it across the depletion layer near the drain junction because they are swept across by the electric field there). We may thus use the limiting value of the drain current in the triode region for $v_{DS} = v_{GS} - V_{t0}$ as being the drain current in the saturation region. Substituting this value in equation (1) we get

$$i_D = \frac{W}{L}\frac{\mu_n C_{ox}}{2}(v_{GS} - V_{t0})^2$$

as the formula for the saturation current. With the identification of KP and K as above, this can be rewritten as

$$i_D = K(v_{GS} - V_{t0})^2$$

which is formula (12.4) of the book.

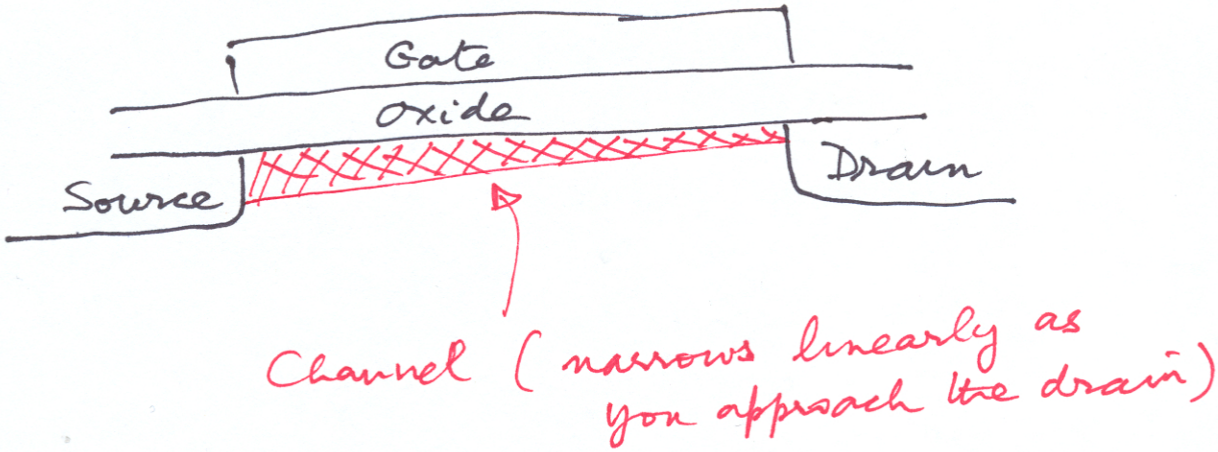

Gate
Oxide
Source
Drain
Channel (narrows linearly as you approach the drain)

Figure 4