MOSFET Overview

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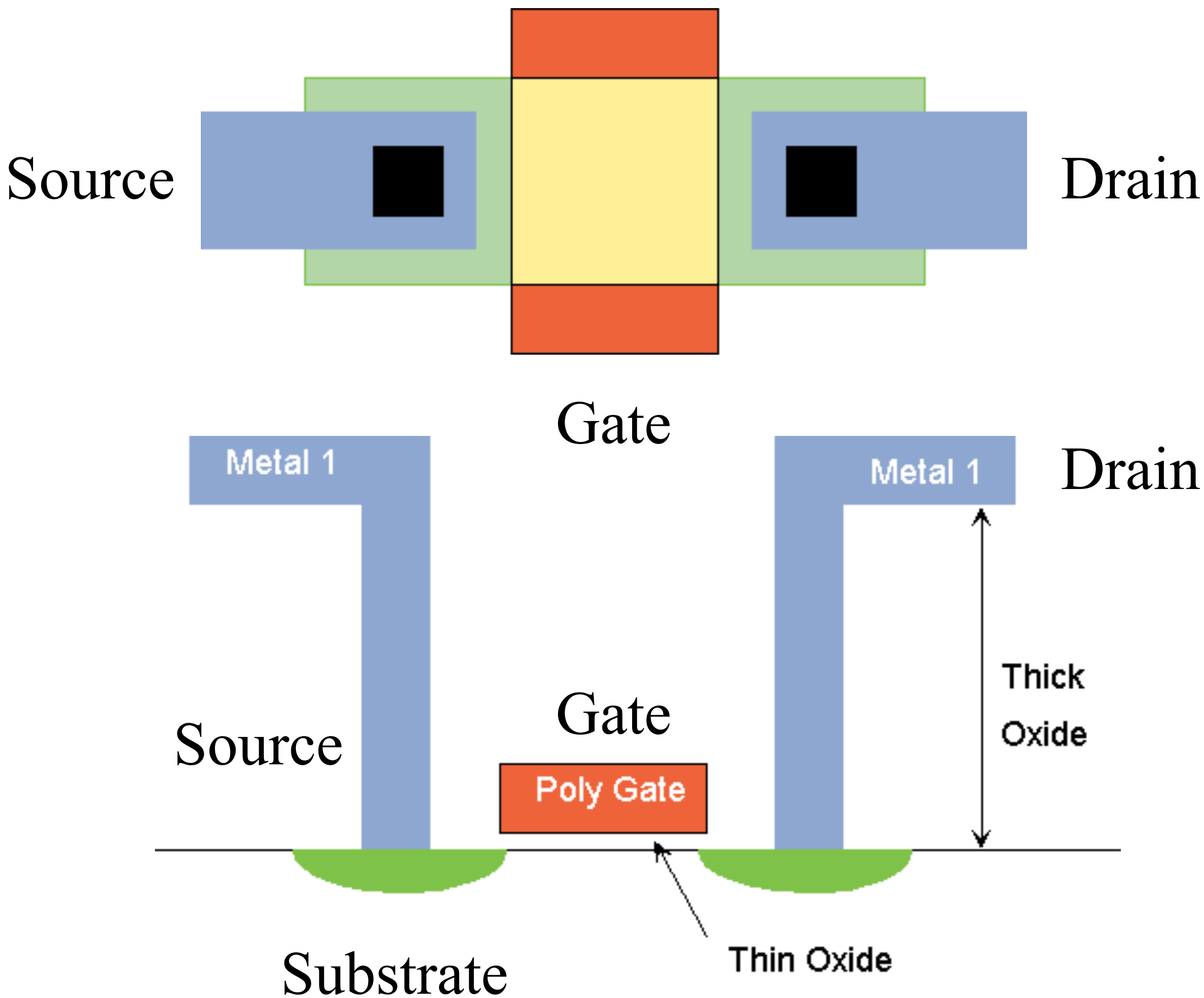
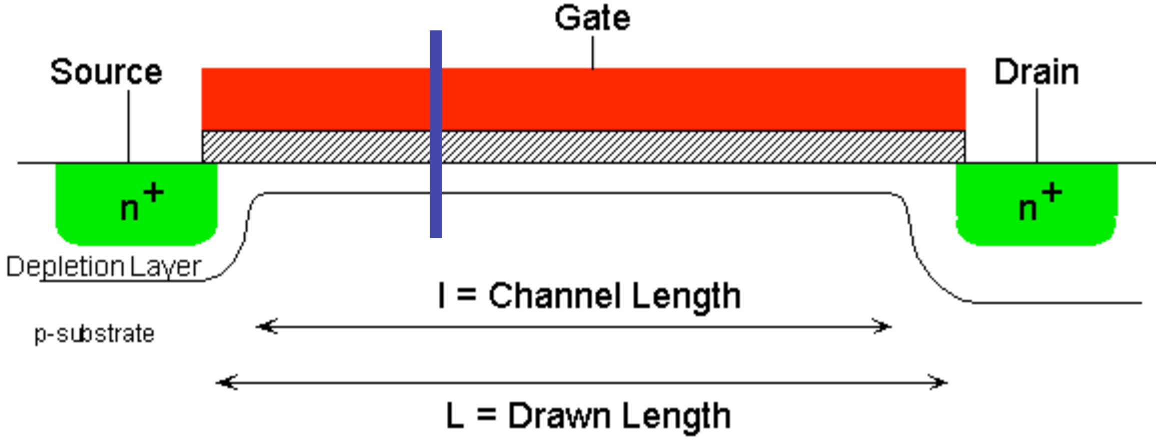
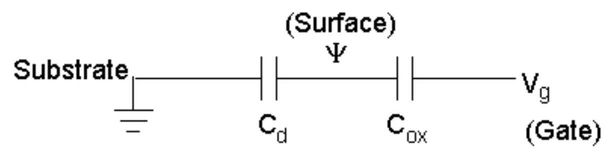
A MOSFET Transistor

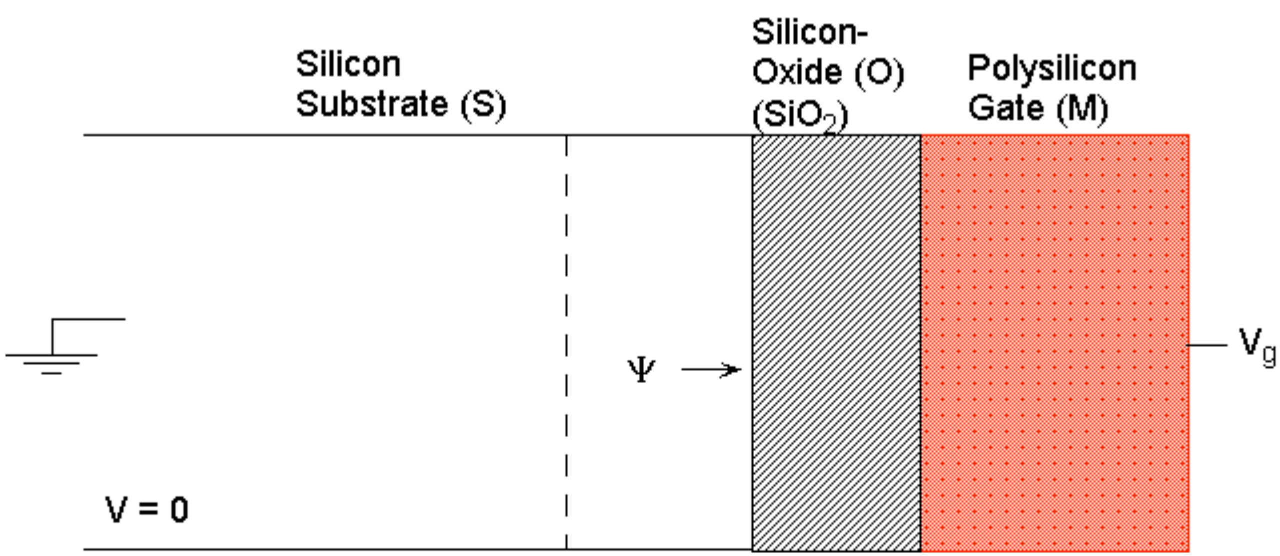


MOS Capacitor Picture

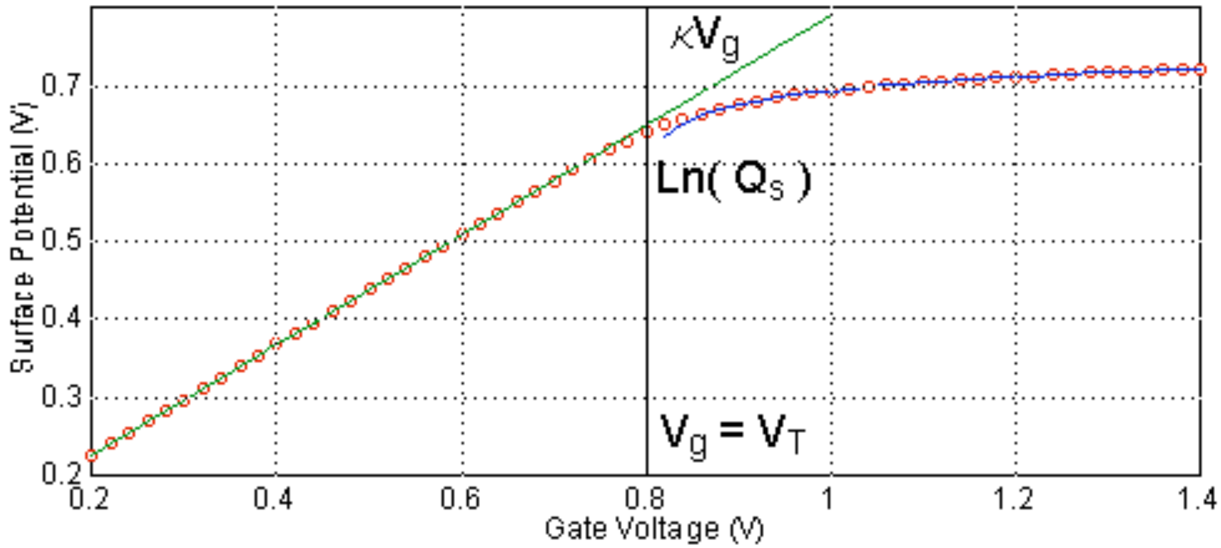




$$\kappa = \frac{\Psi}{V_g} = \frac{C_{ox}}{C_{ox} + C_d}$$



MOS-Capacitor Regions



Surface potential moving from depletion to inversion

$$Q_s = e^{(\Psi - V_s)/U_T}$$

$$Q_s = \ln\left(1 + e^{(\kappa(V_g - V_T) - V_s)/U_T}\right)$$

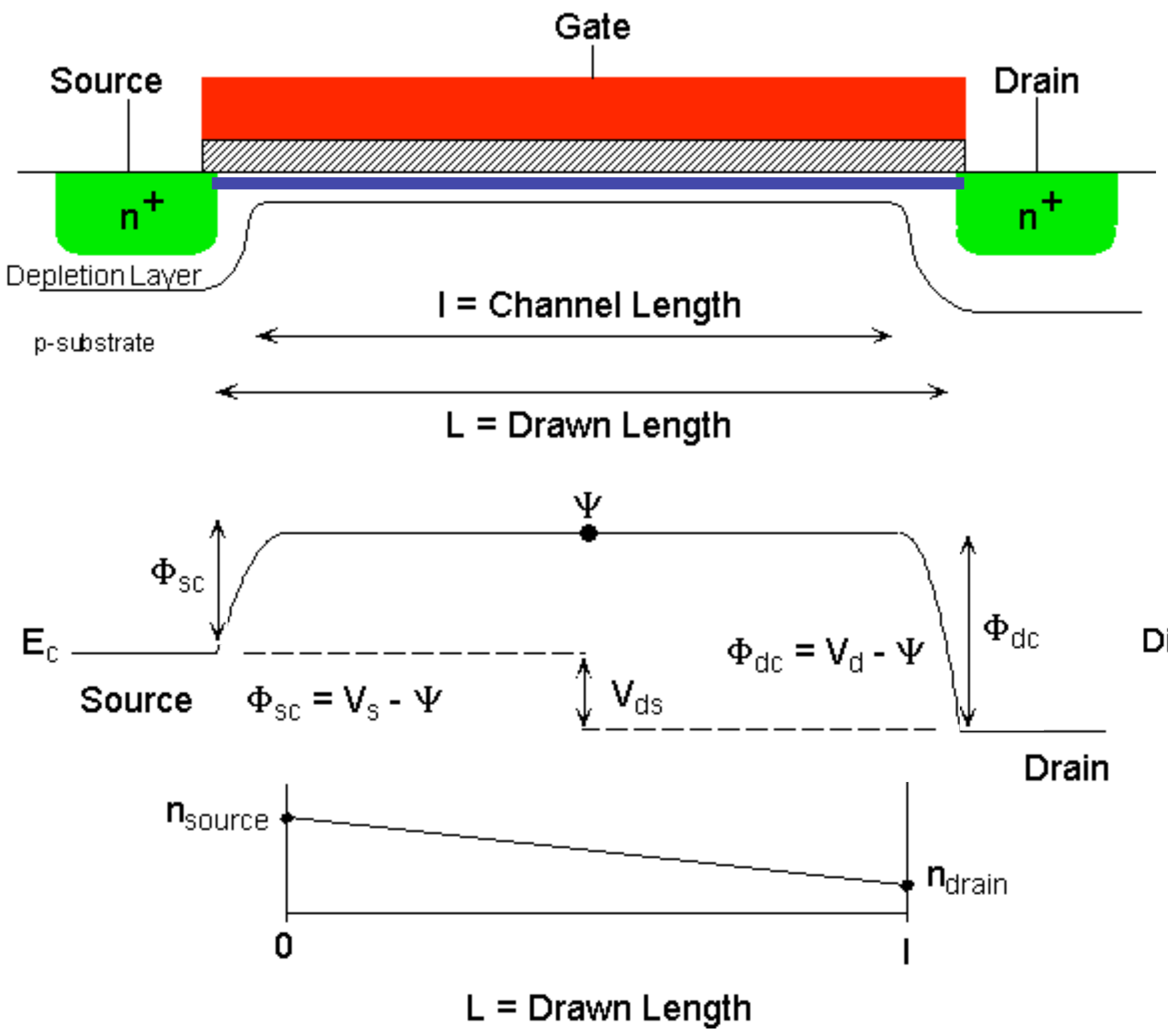
<u>Depletion $(\kappa(V_g - V_T) - V_s < 0)$</u>

$$Q_s = e^{(\kappa(V_g - V_T) - V_s)/U_T}$$

<u>Inversion $(\kappa(V_g - V_T) - V_s > 0)$</u>

$$Q_s = (\kappa(V_g - V_T) - V_s)/U_T$$

MOSFET Channel Picture

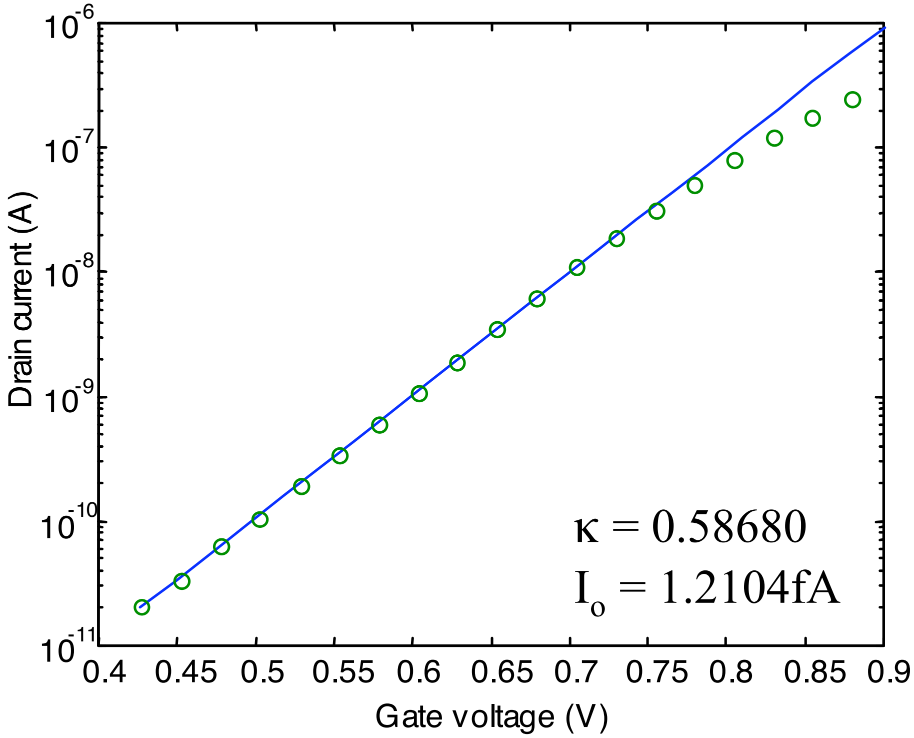


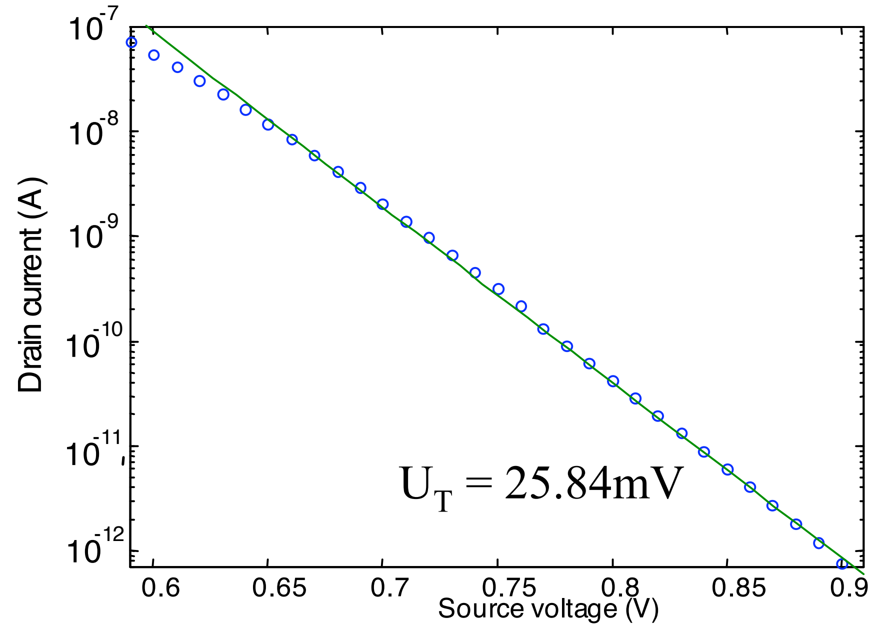
Channel Current is constant

Diffusion: $J_n = q\, D_n \frac{dn}{dx} = q\, D_n \frac{n_{source} - n_{drain}}{l}$

$$I = I_0 \left(e^{\kappa V_g - V_S \;/ U_T} - e^{\kappa V_g - V_d \,/ U_T} \right)$$

Subthreshold MOSFET Curves

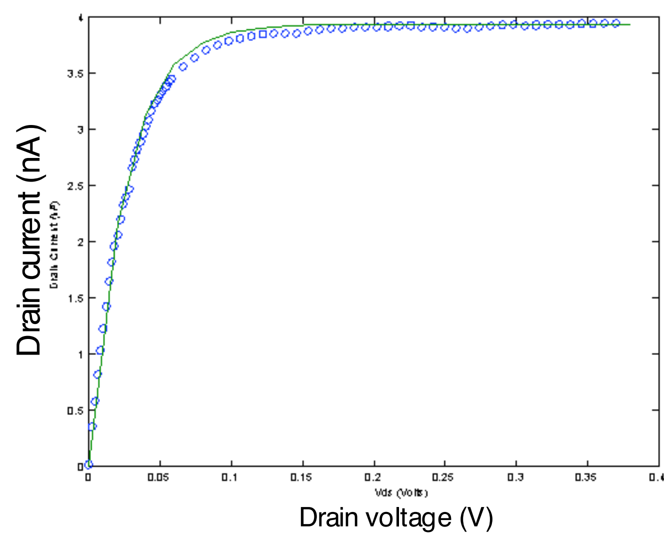




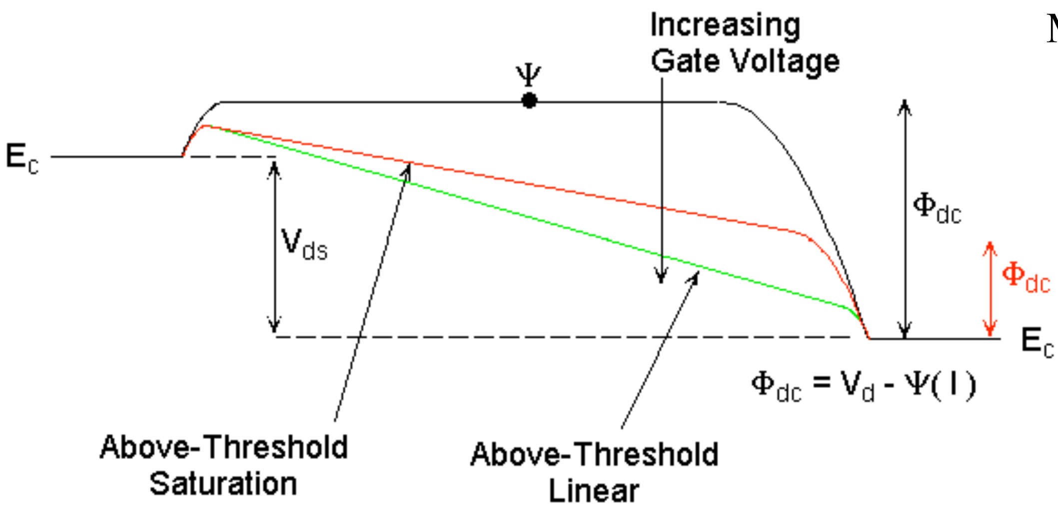
$$I_{ds} = I_o \, e^{\kappa V_g / U_T} \left(e^{-V_s / U_T} - e^{-V_d / U_T} \right)$$

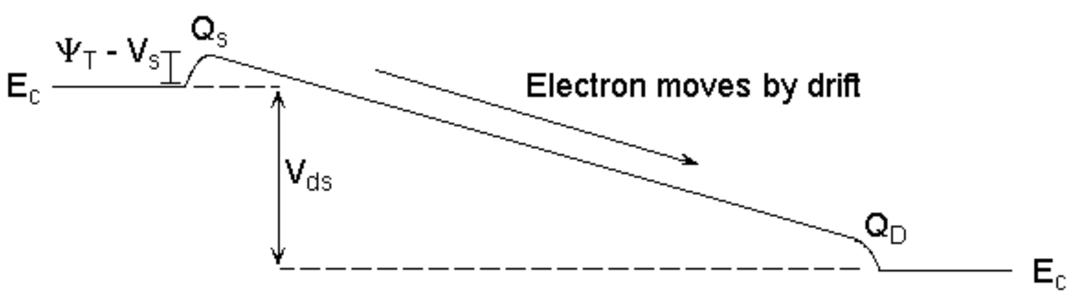
$$= I_o \, e^{(\kappa V_g - V_s) / U_T} \qquad (V_{ds} > 4\, U_T)$$

"Saturation'



Above-Threshold MOSFET





Drift Current: $I = \mu\ Q\ E$

$$Q = \frac{Q_s + Q_D}{2} \qquad E = \frac{Q_s - Q_D}{\varepsilon_{si}}$$

Current is proportional to $(Q_s + Q_D)(Q_s - Q_D) =$

$$Q_s^2 - Q_D^2$$

Moving from subthreshold to above-threshold

Conduction band bends due to electrostatic force of the electrons moving through the channel.

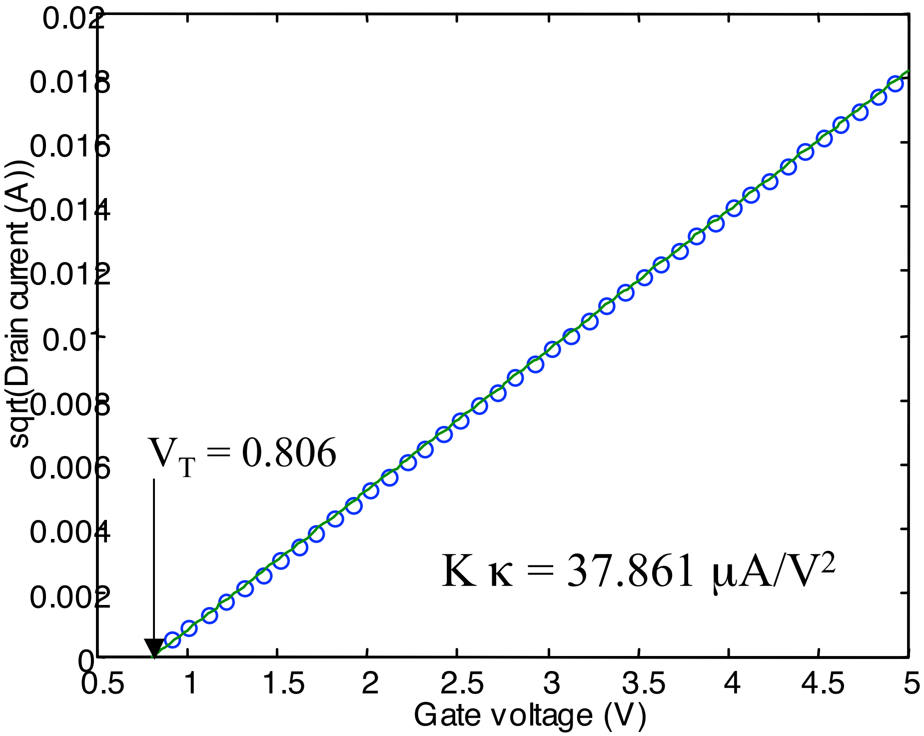
Significant at channel current > I_{th}

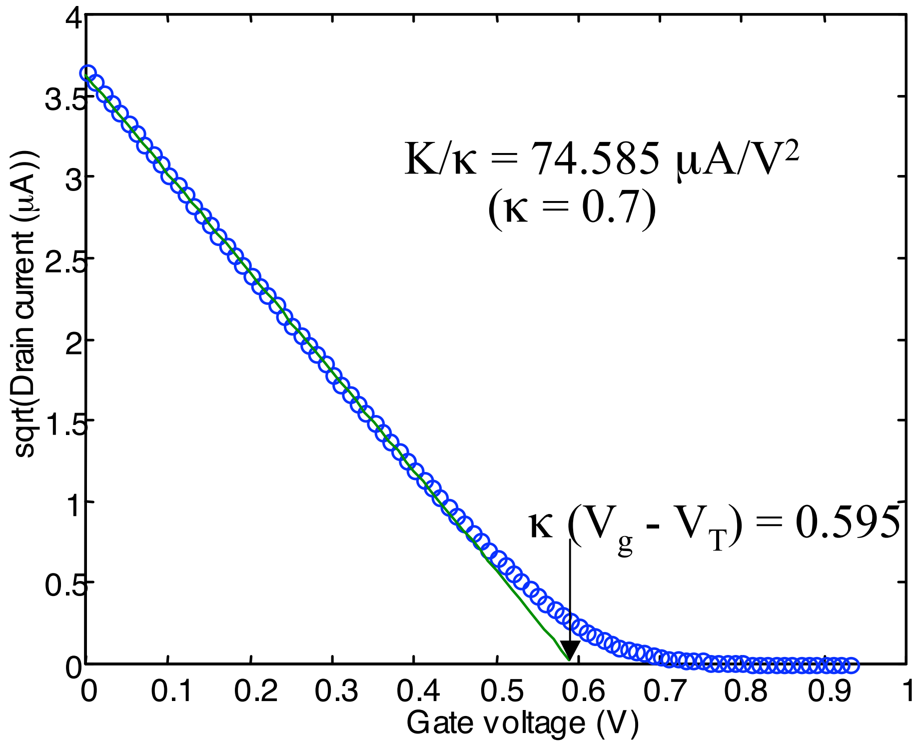
$$I = (K/2\kappa)\ (\ \overbrace{(\kappa(V_g - V_T) - V_s)^2}^{\propto Q_s} - \underbrace{(\kappa(V_g - V_T) - V_d)^{2}}_{\propto Q_d}\ )$$

Saturation: $Q_d = 0$

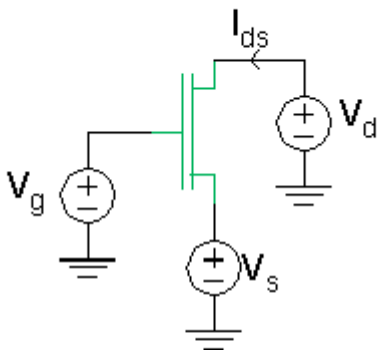
$$I = (K/2\kappa)\ (\ \underbrace{(\kappa(V_g - V_T) - V_s)^2}_{\propto Q_s}$$

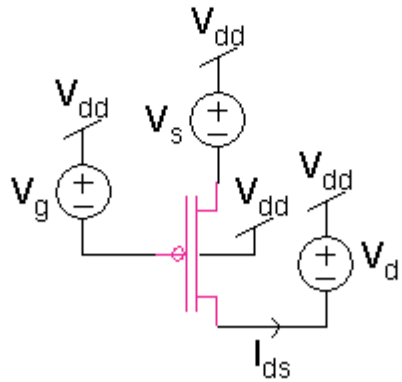
Drain Current - Gate/Source Voltage





MOSFET Equations





Above-Threshold:

$$I = (K/2\kappa)\left((\kappa(V_g - V_T) - V_s)^2 - (\kappa(V_g - V_T) - V_d)^2 \right)$$

Saturation: $(Q_d = 0)$ $\quad I = (K/2)\,(\kappa(V_g - V_T) - V_s)^2$

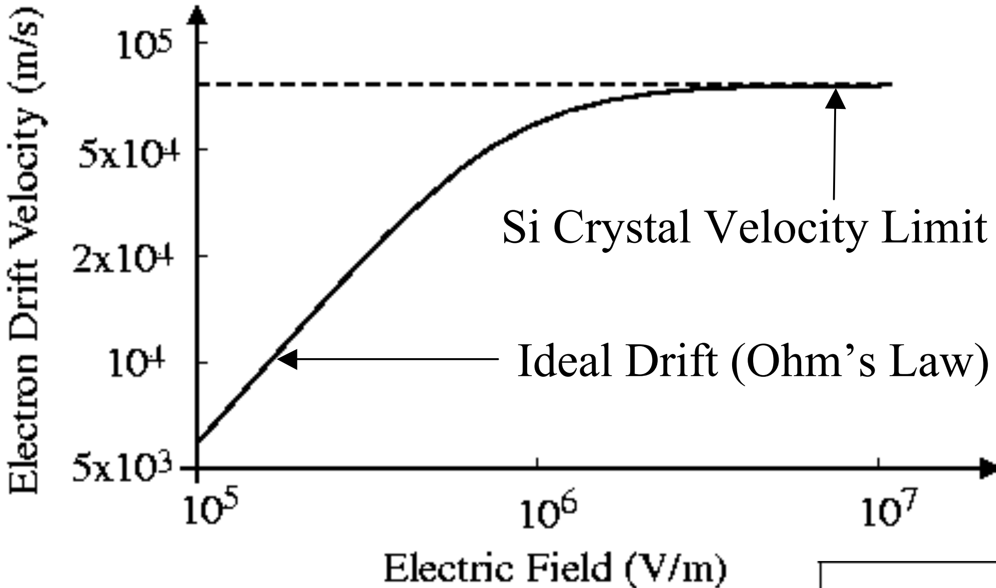
$$V_d > \kappa(V_g - V_T)$$

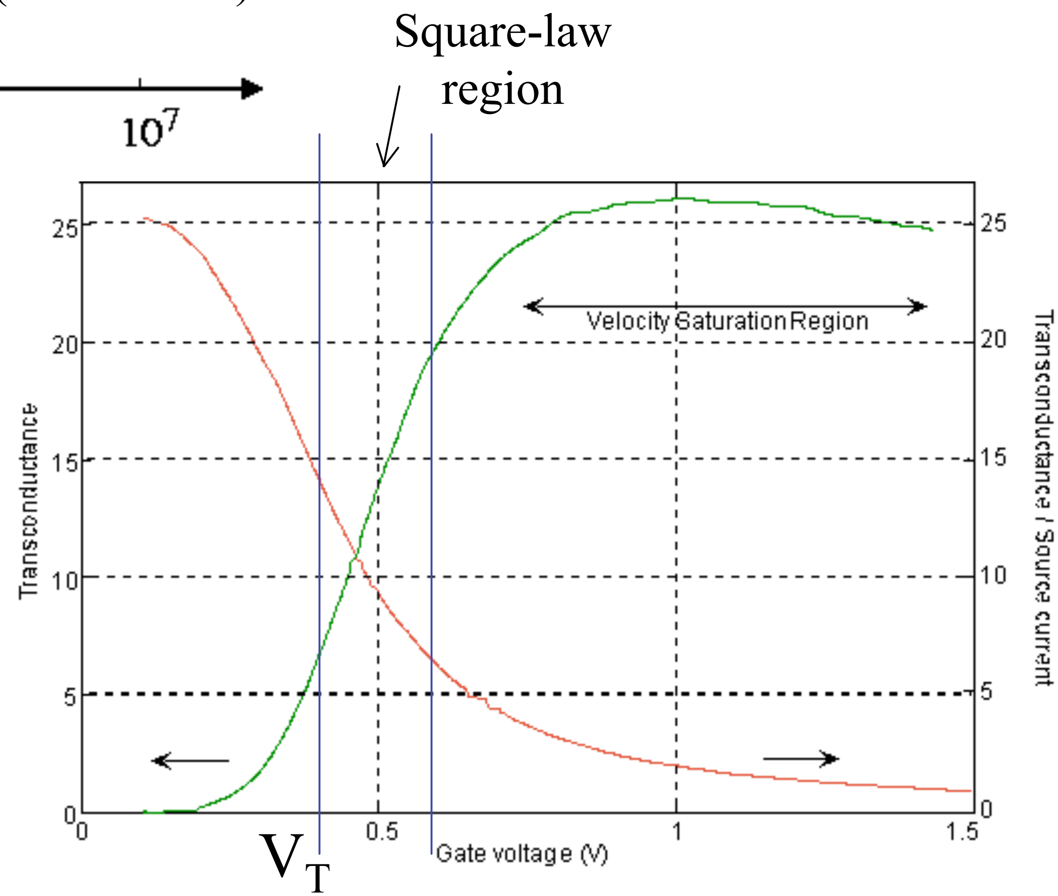
Subthreshold:

$$I = I_s\, e^{\kappa V_g - V_s/U_T}\,(1 - e^{-V_{ds}/U_T})$$

Saturation: $(V_{ds} > 4\,U_T)$ $\quad I = I_s\, e^{\kappa V_g - V_s/U_T}$

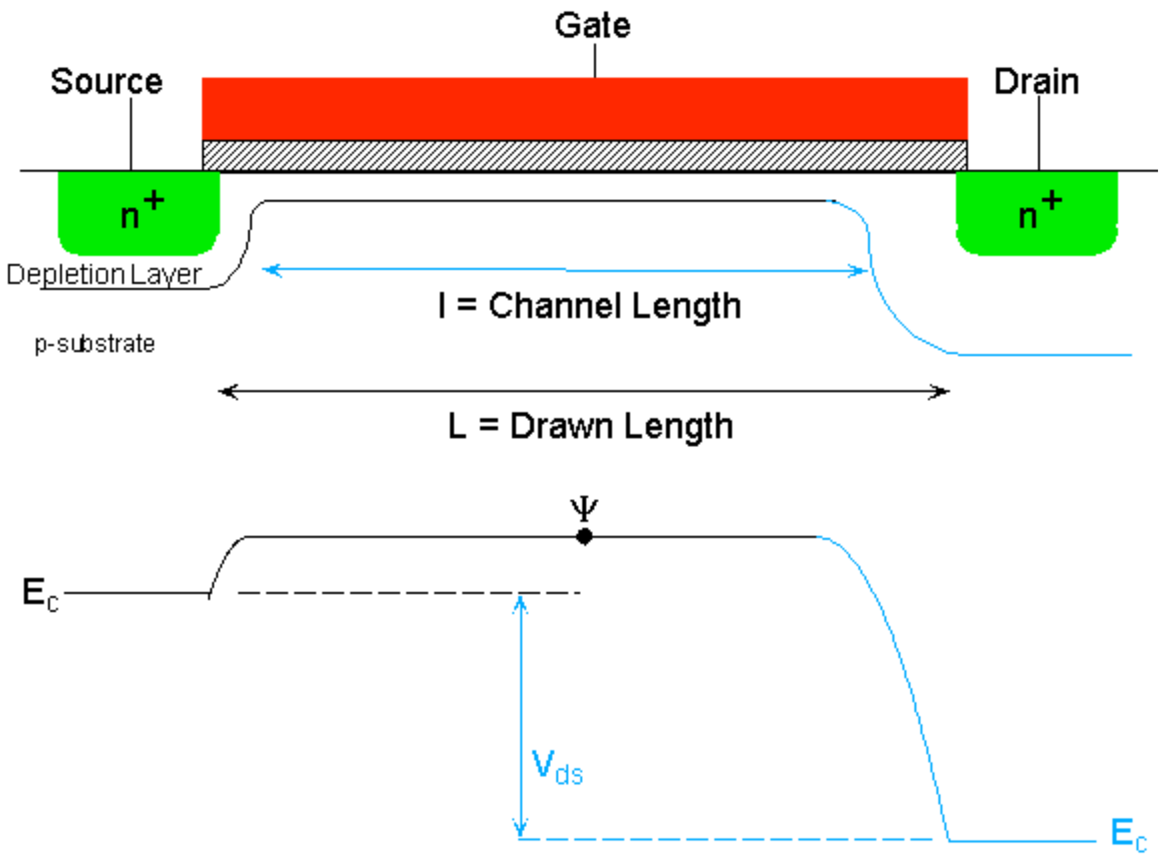
Velocity Saturation





L = 76 nm MOSFET

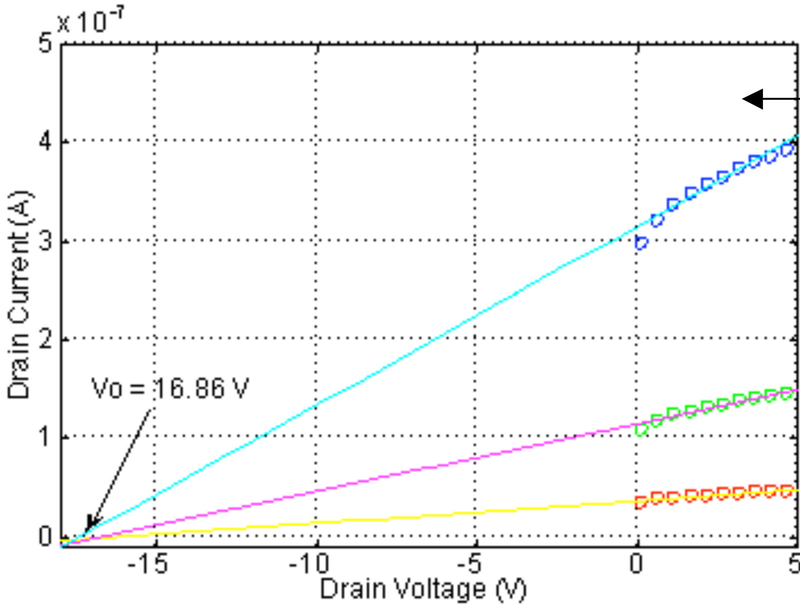
Origin of Drain Dependencies



Increasing Vd effects the drain-to-channel region:

- increases barrier height
- increases depletion width

Current versus Drain Voltage



Why is this not flat?

Effect is called the Early effect
(no, it does not come before something else)

First considered in BJT devices

Limits the gain of a Transistor

$$I_d = I_d(sat)\ (1 + (Vd/Vo))$$

$$I_d = I_d(sat)\ e^{Vd/Vo}$$

$$I_{ds} = I_o\ e^{\kappa V_g / U_T}(e^{-V_s / U_T} - e^{-V_d / U_T})$$

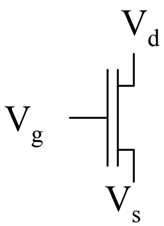
$$= I_o\ e^{(\kappa V_g - V_s)/ U_T} \qquad (V_{ds} > 4\ U_T)$$

"Saturation"

DC-Removed Modeling

Needed for nonlinear analysis; do not want to carry biasing details through the analysis

Formulating the Approach



Assume bias conditions, some set, some set by the circuit:

V_{g0}, V_{d0}, V_{s0}

Resulting in a bias current = I_{bias}

We expand

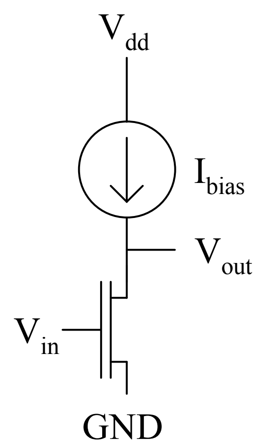
$$V_g = V_{g0} + \Delta V_g,\ V_d = V_{d0} + \Delta V_d,$$
$$V_s = V_{s0} + \Delta V_s$$

For for MOSFET in saturation, we get

$$I = I_0 \exp((\kappa V_g - V_s)/ U_T) \exp(V_d/ V_A)$$
$$= I_{bias} \exp((\kappa \Delta V_g - \Delta V_s)/ U_T) \exp(\Delta V_d/ V_A)$$

$$I_{bias} = I_o \exp((\kappa V_{g0} - V_{s0})/ U_T) \exp(V_{d0}/ V_A)$$

Solving for Transistor Gain



input/output relationship?

- Transitor in saturation

$$I_{bias} = I_{bias}\exp(\kappa\Delta V_{in}/ U_T) \exp(\Delta V_{out}/V_A)$$

$$\text{Gain} = \Delta V_{out} / \Delta V_{in} = - \kappa V_A / U_T$$

Key parameters of EKV model

$K' \longrightarrow Kp$

$\kappa \longrightarrow \gamma$, $2\phi_f$ $\quad \gamma = 1 / (2\kappa \sqrt{2\phi_f})$

$V_{T0} \longrightarrow V_{T0}$ (not voltage dependant)

$V_A \longrightarrow DL$, λ

and some short-channel parameters