# I) MOSFET

Metal-Oxide-Semiconductor-Field-Effect-Transistor

- most ~~usually~~ widely used semiconductor devices

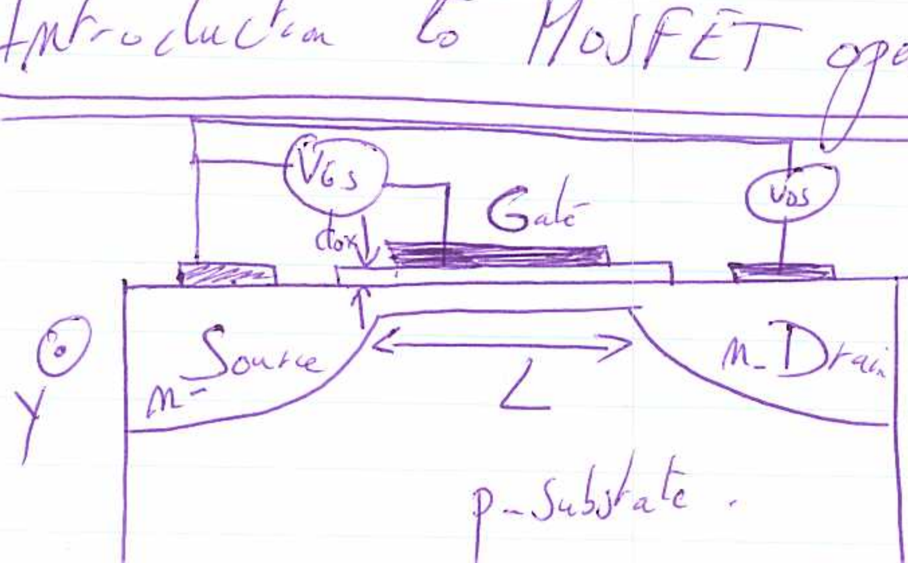
[Figure 7.1 of textbook → Moore's law; exponential growth of integration density with time.

- 2 types of MOSFET
  - → n-channel MOSFET or nFET
  - → p-channel MOSFET or pFET

[The most commonly used technology is CMOS (Complementary MOS) in which both n-channel and p-channel transistors are fabricated.

- we limit here our analysis to nFET where ~~we responsible~~ the current flow is due to $e^-$.

## 1) Introduction to MOSFET operation



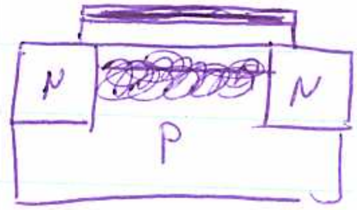

L = channel length

$d_{ox}$ = oxide thickness

W = channel width in Y direction

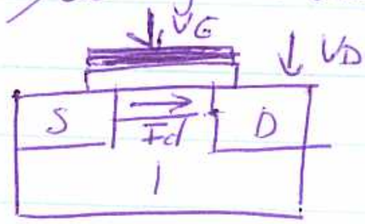
operation principles

* Transistor is "off" state




* Applying a voltage $V_T$ to the gate "inverts" the channel region creating an electrical path between the source and drain.

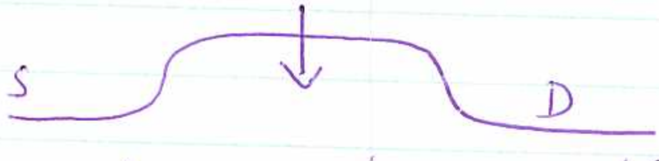

* Applying a voltage to the Drain pulls current carriers across the channel, creating the drive current ($I_D$)




## * The role of gate electrode for n-channel MOSFET

Positive gate voltage does two things-

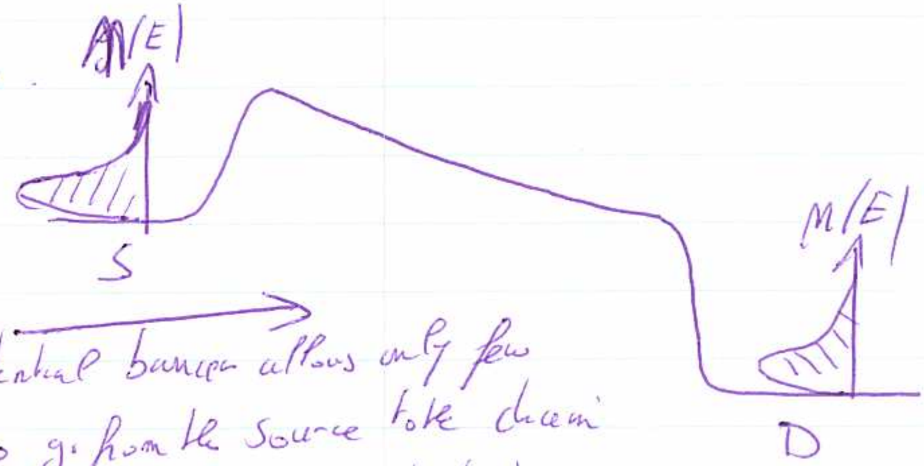
(1) Reduces the potential energy barrier seen by the $e^-$ from the source and the drain region




(2) Inverts the surface, and increases the conductivity of the channel.

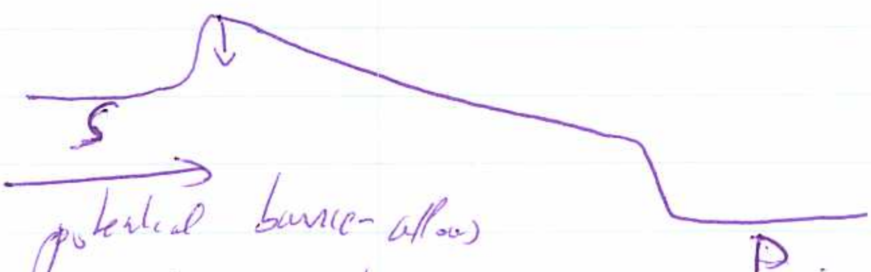
## * The role of the Drain electrode for n-channel MOSFET

$V_G = 0$, $V_D > 0$.




Large potential barrier allows only few $e^-$ to go from the source to the drain (subthreshold conduction).

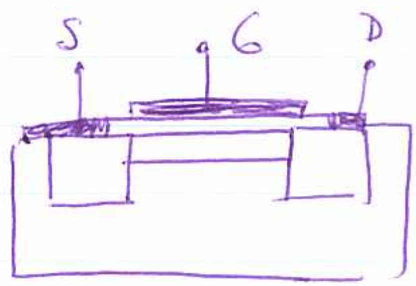
$V_G > 0$, $V_D > 0$.




Smaller potential barrier allows a large number of $e^-$ to go from the source to the drain.

## * Qualitative description of MOSFET operation

(a) $V_G > V_T$, $V_D > 0$ (small)

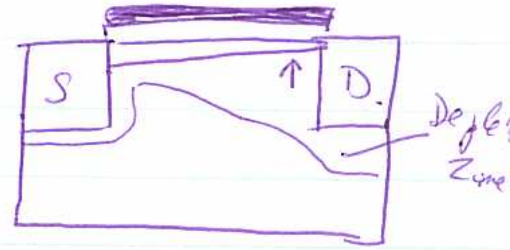



Variation of $e^-$ density along the channel is small

$I_D \sim V_D \Rightarrow$ linear regime

(b) $V_G > V_T$, $V_D > 0$ (large).

Increase in the drain current reduce due to the reduced conductivity of the channel at the drain end

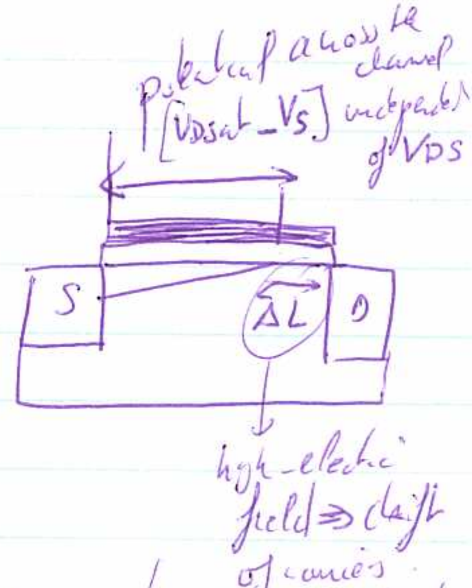



(c) $V_G > V_T$, $V_D = V_{Dsat}$
Drain saturation voltage.

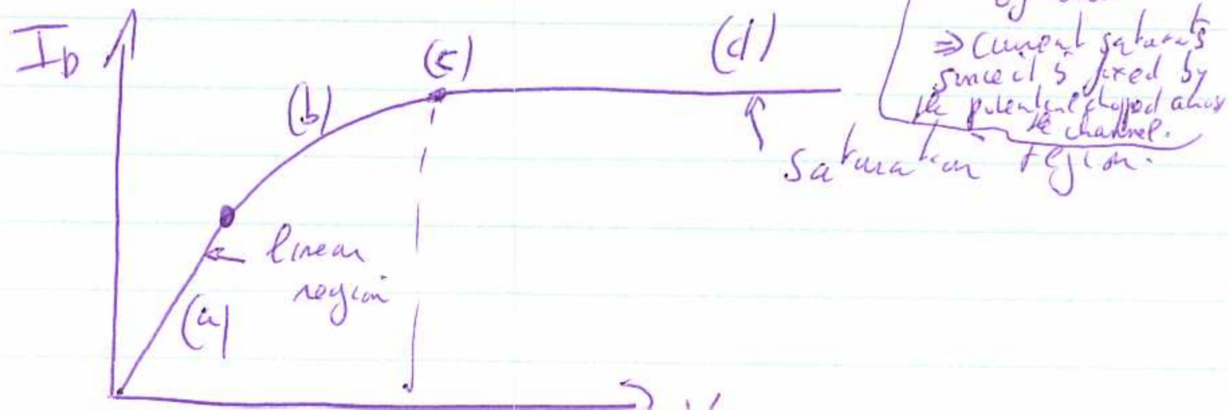
Pinch-off point: $e^-$ density at the end channel is identically zero.

(d) $V_G > V_T$; $V_D > V_{Dsat}$

Post pinch-off characteristic.
The excess drain voltage is dropped across the highly resistive pinch-off region denoted by $\Delta L$




⇒



# 2 MOSFET analysis

## a The linear Model

it describes the behavior of a MOSFET biased with a small drain-to-source voltage.

* MOSFET acts as a linear device ⇒ can be modeled as a linear resistor whose resistance is modulated by the gate voltage.

General expression for the Drain current.

$$I_D = -\frac{Q_{inv} WL}{t_r}$$

$Q_{inv}$ = inversion layer charge per unit of area.

$W$ = gate width

$L$ = gate length.

$t_r$ = transit time $\quad \boxed{t_r = \frac{L}{v}}$ $v$ = velocity

$$\boxed{v = \underbrace{\mu}_{\text{mobility}} \underbrace{\mathcal{E}}_{\text{electric field}} = \mu \frac{V_{DS}}{L}}$$

$$\Rightarrow \boxed{I_D = -\mu Q_{inv} \frac{W}{L} V_{DS}}$$

we saw that (MOS capacitor) $V_G = V_T - \frac{Q_{inv}}{C_{ox}}$

$\Rightarrow \boxed{Q_{inv} = -C_{ox}(V_G - V_T)}$ if $V_G > V_T$

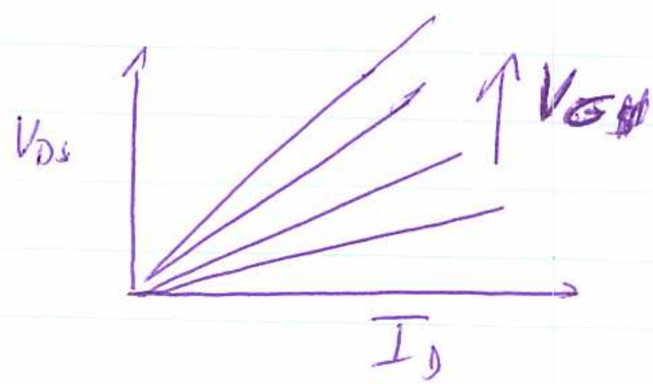
with $\boxed{V_T = V_{FB} + V_S + \frac{\sqrt{2\epsilon q N_A V_S}}{C_{ox}}}$ $V_S = 2V_F$

so $\boxed{I_D = \mu C_{ox} \frac{W}{L}(V_G - V_T) V_{DS}}$

for $|V_{DS}| << (V_G - V_T)$

* Also $I_D = 0$ if $V_G < V_T$.

* $|V_{DS}| << (V_G - V_T) \Rightarrow$ means that $N$, $E$, $Q_{inv}$ is constant between source and drain.




## (b) The quadratic model

the model for the charge includes the voltage variation between source and drain. the variation of the depletion layer charge is ignored, not the variation of the inversion layer charge.
it is the most commonly used model.

[the charge on the gate is completely balanced by $Q_N(x)$
$Q_N(x) \simeq -C_{ox}(V_G - V_T - V_c(x))$]

We consider a small section with width $dy$, and channel voltage $V_c$.

~~$V_{GS} \Rightarrow V_{GS} - V_c$ inside the channel. since~~

so the previous expression from the linear model becomes

$$\boxed{I_D = \mu C_{ox} \frac{W}{dy} (V_G - V_c - V_T)\, dV_c}$$

where $\left[\begin{array}{l} L \to dy \\ V_{DS} \to dV_c \end{array}\right.$ locally

Integrating from Source to Drain.

$$\int_0^L I_D\, dy = \mu C_{ox} W \int_0^{V_{DS}} (V_G - V_c - V_T)\, dV_c$$

$I_D$ is constant along the channel so $\Longrightarrow$

$$\boxed{I_D = \mu C_{ox} \frac{W}{L} \left[ (V_G - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]} \quad (*)$$

$V_{DS} < V_{GS} - V_T$

the Drain current first increases linearly with the applied drain to source voltage, but then reaches a maximum value.

if $\boxed{V_{DS} = V_G - V_T} \equiv V_{DS,sat} \quad \left[ \frac{dI_D}{dV_{DS}} = 0 \right]$

Drain saturation voltage $V_{DS,sat}$

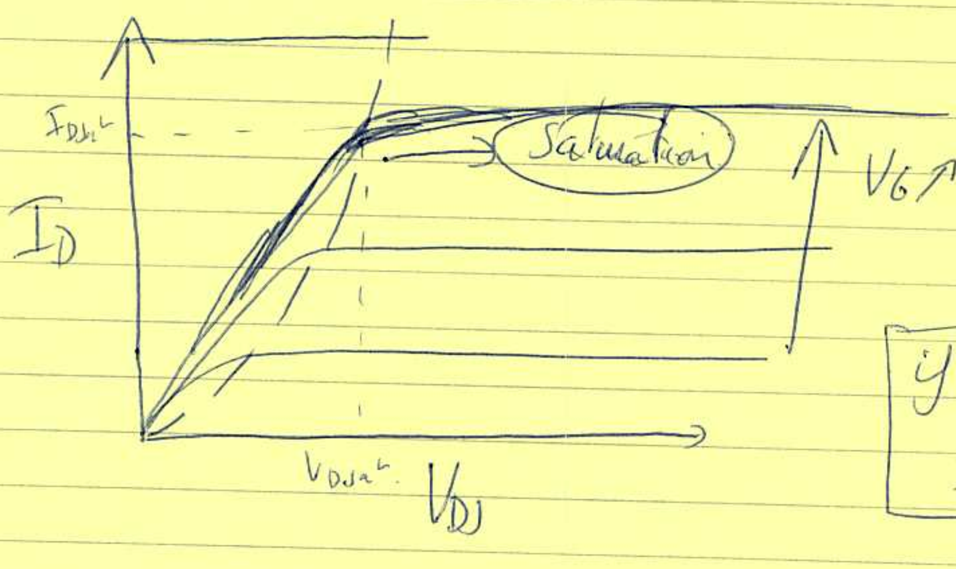
We call $I_{D,satt}$, the value of the saturated drain current. $\Rightarrow$ pinch-off point. $Q_{inv} = 0$ at the Drain interface

$$\Rightarrow \boxed{I_{D,SAT} = \mu C_{ox} \frac{W}{L} \frac{(V_{GS} - V_T)^2}{2}}$$

The equation (*) is not valid beyond the pinch-off point

if $\boxed{V_{DS} > V_{GS} - V_T}$ $\Rightarrow$ the current maintains the value $I_{D,SAT}$.

The quadratic model explains the typical I–V characteristics of a MOSFET, which are normally plotted for different $V_{GS}$.




$\boxed{\text{if } V_{GS} < V_T \quad I_D = 0}$

* We would like to calculate the transconductance $g_m$ and
(i) the ~~output~~ transconductance $g_m$ is given by

$$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}\ cte} \quad \left(\text{if } g_m \nearrow \text{ Speed of the device} \nearrow\right)$$

Here we get in the quadratic region $\boxed{g_{m,quad} = \mu C_{ox} \frac{W}{L} V_{DS}}$ if $V_{DS} < V_{GS} - V_T$

In saturation $\boxed{g_{m,sat} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T)}$

(ii) the output conductance $g_d$ is given by

$$g_d = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_{GS}}$$

[" ease with which an electric current flows through a material" → reciprocal of resistance ]

$$\boxed{g_d = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T - V_{DS})}$$ [in the quadratic region.]

$g_d \searrow$ if $V_{DS} \nearrow$.

and $g_d \to 0$ as the device operated in the saturated region $\boxed{g_{d,sat} = 0.}$