Part IV Transistors

I MOSFET

Metal_ Oxide_ Semiconductor_ Field_ Effect_ Transistor

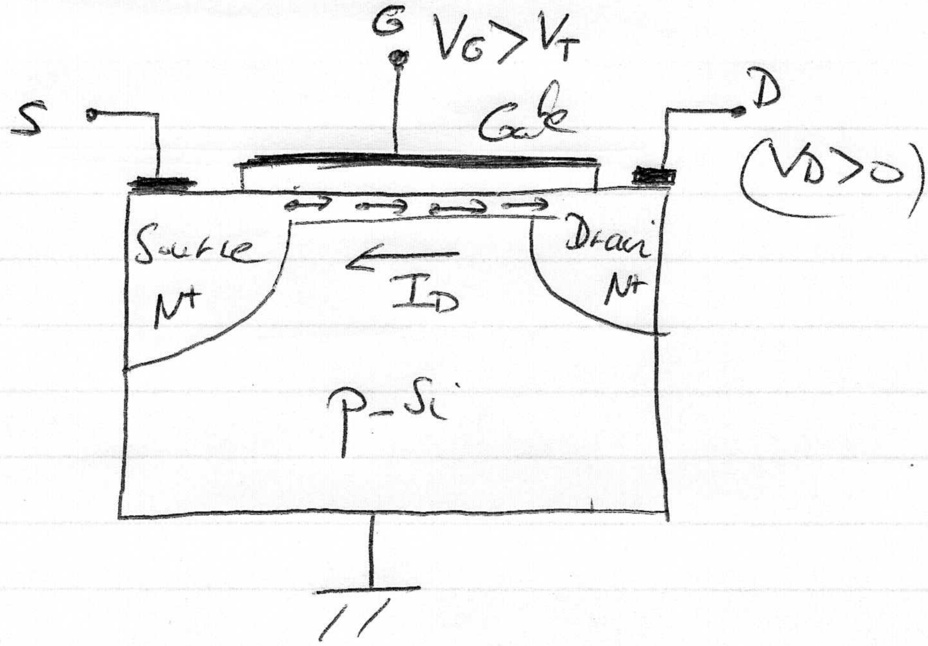
Most widely used SC devices.

2 types of MOSFET → n-channel MOSFET, nFET
↳ p-channel MOSFET, pFET.

The most commonly used device is CMOS (complementary MOS) in which both n-channel and p-channel transistors are fabricated

⇒ we limit here our analysis to ~~MOSFET~~ nFET where the current flow is due to $\bar{e}$.

See Fig 17.1



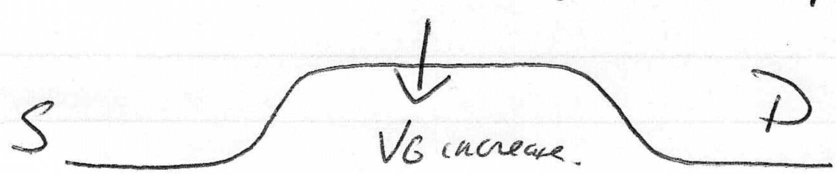
1 Introduction

(a) The role of the gate electrode

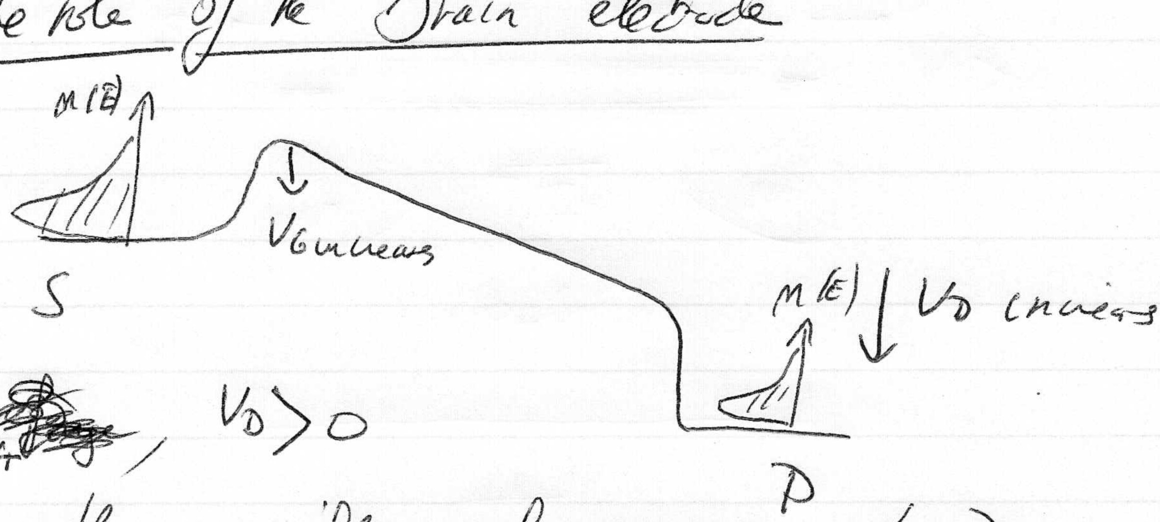
Positive gate voltage does two things.

(i) Invert the surface (if $V_G > V_T$) and increases the conductivity of the channel.

(ii) Reduces the potential energy barrier seen by the e^- from the source to the Drain region. (~~[illegible]~~)



(b) The role of the Drain electrode



if $V_G > V_T$, $V_D > 0$

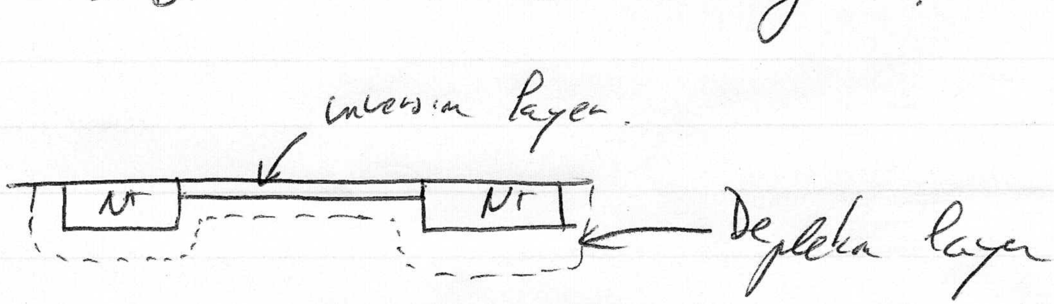
$\bar{e}$ can then flow from Source to Drain.

(c) MOSFET operations Fig. 17.2

$V_G > V_T$

(a) $V_D > 0$ (small)

Variation of the electron density along the channel is small $I_D \sim V_D \Rightarrow$ linear regime.

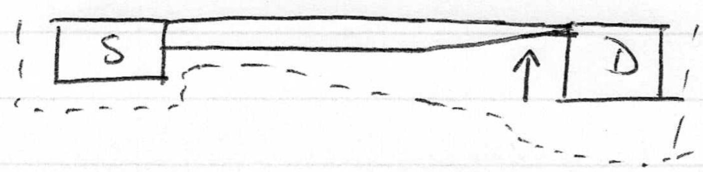


(b) $V_D > 0$ (larger)

increase in the Drain current

is reduced to the reduced conductivity of

the channel at the drain end.



(c) $V_D = V_{Dsat}$ Drain saturation voltage.

$\Rightarrow$ Pinch off point : e^- density at the end

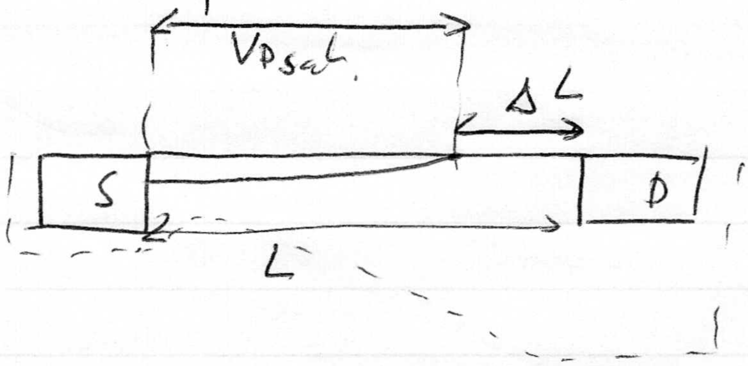
channel is identically zero

(d) $V_D > V_{Dsat}$ $\Rightarrow$ Post pinch-off characteristic

The excess drain voltage is dropped across the highly

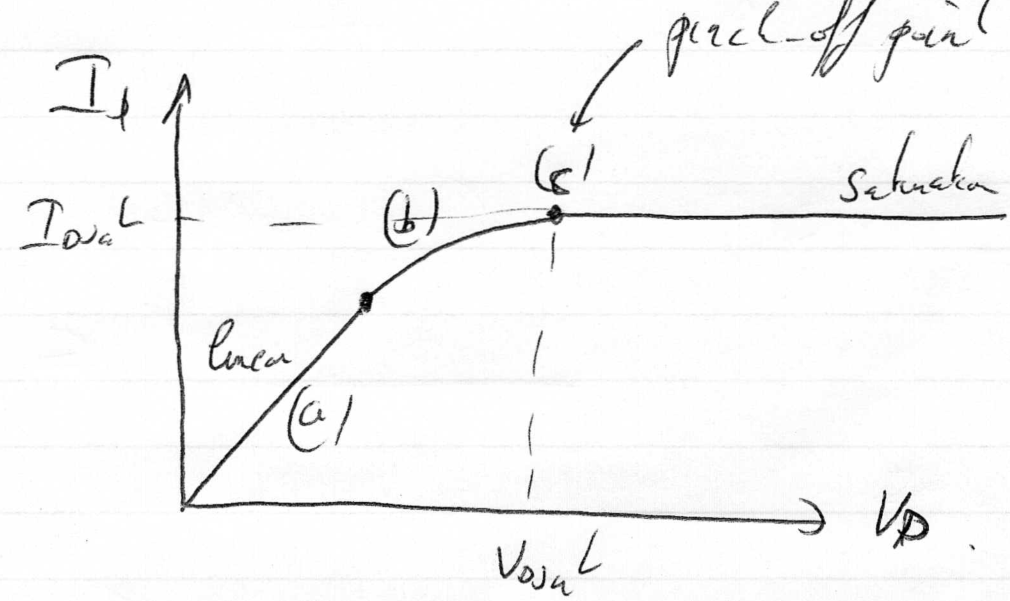
resistive pinch-off region denoted by ΔL.

potential across the channel independent of V_{DS}



the current saturates since it is fixed by the potential dropped across the channel V_{Dsat}.

Fig 17.3



2 MOSFET analysis

a The linear model

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

MOSFET acts as a linear device $\Rightarrow$ can be modeled as a linear resistor whose resistance is modulated by the gate voltage.

general expression for the Drain current.

$$I_D = -\frac{Q_{inv} W L}{t_r}$$

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

W = gate width.

L = gate length

t_r = transit time

$$\boxed{t_r = \frac{L}{v}}$$

v = velocity.

$$\boxed{v = \mu \mathcal{E} = \mu \frac{V_{DS}}{L}}$$

mobility   electric field

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

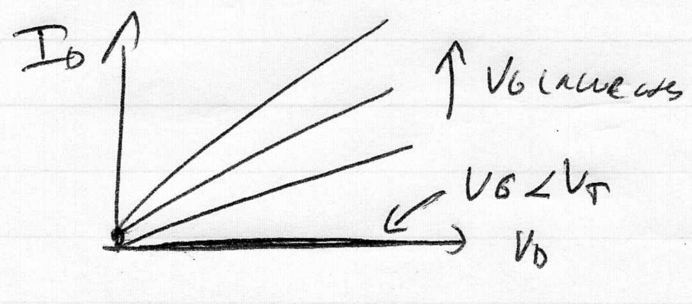
we saw in the MOS capacitor section that

$$V_G = V_T - \frac{Q_{inv}}{C_{ox}} \qquad \text{if } V_G > V_T$$

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

Finally $$\Rightarrow \boxed{I_D = \mu C_{ox} \frac{W}{L} (V_G - V_T) V_D}$$

- if V_D is small $|V_D| \ll |V_G - V_T| \Rightarrow \mu$, $\mathcal{E}$ and Q_{inv} are expected constant between source and drain
- also $I_D = 0$ if $V_G < V_T$



① The quadratic model. (Square-Law theory)

the model include the voltage variation between Source and Drain for the ~~charge~~ inversion layer charge.

$$\boxed{Q_{inv}(x) \simeq -C_{ox}\left(V_G - V_T - V(x)\right)} \quad 17.16$$

$V(x)$ is the electrostatical potential in the channel due to the Source - Drain voltage.

$$V(x) = \begin{cases} 0 \text{ if } x = 0 \\ V_D \text{ if } x = L \end{cases}$$

In this model V_T is independent of x, this mean that the variation of the depletion charge is ignored.

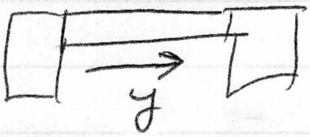
⟹ most commonly used model

in the linear model, we obtained

$$I_D = \mu C_{ox} \frac{W}{L}(V_G - V_T) V_D. \qquad \underline{V_G > V_T}$$

Let us consider that the linear model is valid locally.

$$\begin{cases} L \to dy \\ V_D \to dV \end{cases}$$



also $V_G - V_T \Rightarrow V_G - V_T - V$

$$\Rightarrow \boxed{I_D = \mu C_{ox} \frac{W}{dy}(V_G - V_T - V)\, dV}$$

integration from source to Drain.

$$\underbrace{\int_0^L I_D\, dy}_{\Rightarrow L I_D} = \mu C_{ox} W \underbrace{\int_0^{V_D} (V_G - V_T - V)\, dV}_{(V_G - V_T) V_D - \frac{V_D^2}{2}}.$$

since I_D is constant along the channel.

we obtain

$V_G > V_T$ $$\boxed{I_D = \mu C_{ox} \frac{W}{L}\left[(V_G - V_T)V_D - \frac{V_D^2}{2}\right]}$$ $\boxed{17.17}$ ($W = Z$)

the Drain current increases linearly with the applied V_D potential, but then reaches a maximum value.

(17.21) $$\boxed{V_D = V_G - V_T \equiv V_{D,sat}}$$

obtain using $\left(\frac{dI_D}{dV_D} = 0\right)$

Drain saturation voltage.

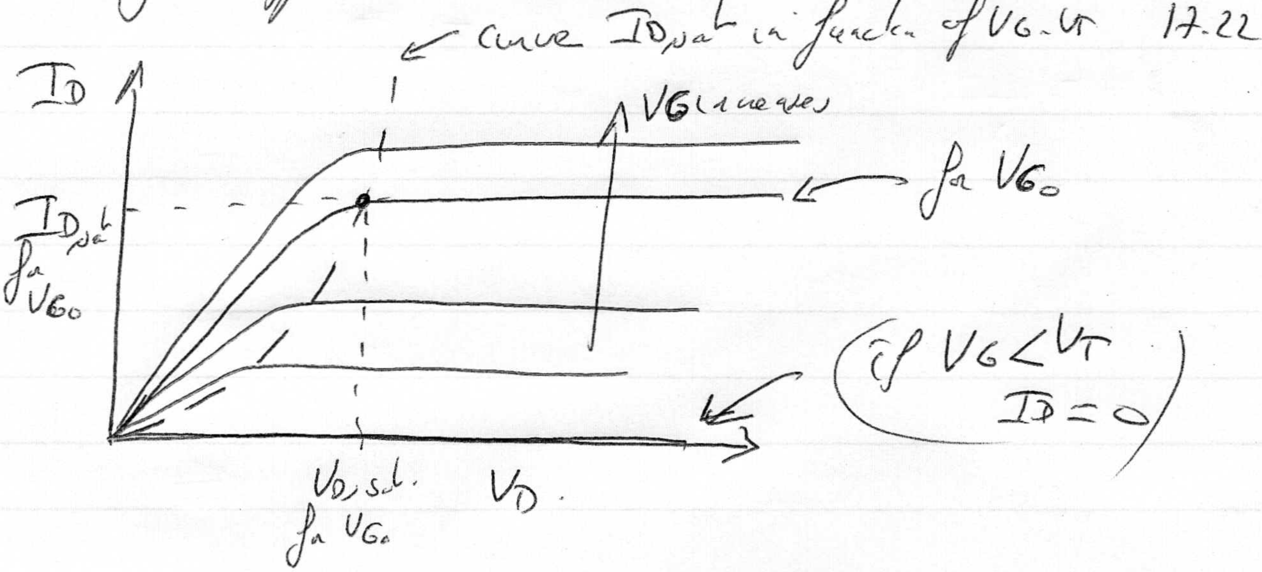
we call $I_{D,sat}$ the value of the saturated Drain current $\Rightarrow$ pinch-off point at $V_{D,sat}$.

$$\boxed{I_{D,sat} = \mu C_{ox} \frac{W}{L} \frac{(V_G - V_T)^2}{2}}$$ (17.22)

the equation (17.17) is not valid beyond the pinch-off point

if ($V_{DS} > V_G - V_T$) ⇒ the current maintain the value $I_{D,sat}$.

the quadratic model explains the typical I–V characteristics of a MOSFET, which are normally plotted for different V_G



* ~~[illegible]~~

c) The variable depletion layer - (Bulk-Charge theory)

in the quadratic model, we have.

$$Q_{inv(x)} = -C_{ox}\left(V_G - V_T - V(x)\right) \qquad V_G > V_T$$

where $$V_T = V_{FB} + \cancel{2}V_S + \frac{\sqrt{2 \epsilon q N_A V_S}}{C_{ox}} \qquad V_S = 2V_F$$

due to depletion layer charge.

in this model we account for the variation of the depletion layer $\Rightarrow$ $$\boxed{V_{T(x)} = V_{FB} + V_S + \frac{\sqrt{2\epsilon q N_A (V_S + V(x))}}{C_{ox}}} \qquad V_S = 2V_F$$

finally

$$\boxed{Q_{inv} = -C_{ox}\left(V_G - V_T(x) - V(x)\right)}$$

(17-23)

(it is an approximation)

$\Rightarrow$ after calculation (integration).

17.28

it is an approximation

$$\boxed{I_D = \mu C_{ox} \frac{W}{L}\left(V_G - V_{FB} - 2V_F - \frac{V_D}{2}\right) V_D - \frac{2}{3} \mu \frac{W}{L} \sqrt{2\epsilon q N_A}\left[(2V_F + V_D)^{3/2} - (2V_F)^{3/2}\right]}$$

we will use

$$\boxed{I_D = \mu C_{ox} \frac{W}{L} \left\{ \left(V_G - V_{FB} - 2V_F - \frac{V_D}{2}\right) V_D - \frac{2}{3} \gamma \left[(2V_F + V_D)^{3/2} - (2V_F)^{3/2} \right] \right\}}$$

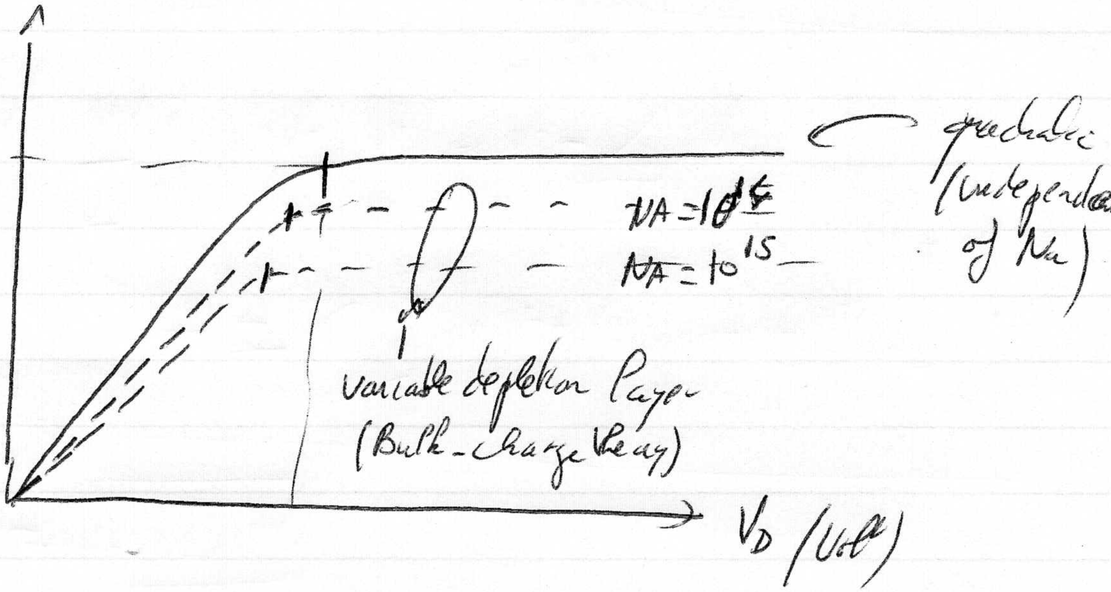
with $\gamma = \frac{\sqrt{2 q \varepsilon_{Si} N_a}}{C_{ox}}$

Again this expression is not valid after the pinch-off point for describing the saturation regime.

$$\boxed{V_{Dsat} = V_G - V_{FB} - 2V_{FB} + \frac{\gamma^2}{2} - \gamma \sqrt{V_G - V_{FB} + \frac{\gamma^2}{4}}}$$

⇒ the quadratic model yields to larger current compared to more accurate derivation like the variable depletion layer model.

See Fig 17.9



d) Conductance and transconductance

Transconductance g_m.
$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D \text{ constant}}$$

if $g_m \nearrow \Rightarrow$ speed of the device $\nearrow$

quadratic model (square-law theory)

$$\boxed{g_m = \mu C_{ox} W \frac{V_D}{L}}$$

in saturation

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

Variable depletion model (bulk-charge theory)

$$\boxed{g_m = \mu C_{ox} \frac{W}{L} V_D}$$ still

in saturation

$$\boxed{g_{m,sat} = \mu C_{ox} \frac{W}{L} V_{Dsat}}$$

almost linear with V_G

Conductance g_d is given by

$$g_d = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G \text{ constant}} \Rightarrow$$

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

quadratic model

$$\boxed{g_d = \mu C_{ox} \frac{W}{L} (V_G - V_T - V_D)}$$

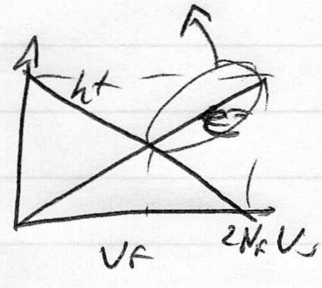
$g_d \searrow$ if $V_D \nearrow$

Also $g_d \to 0$ as the device operated in the saturated Region $\boxed{g_{d,sat} = 0}$

3 Subthreshold current

So far, we assumed that $I_D = 0$ if $V_G < V_T$.
Actually there is a significant amount of e^- near the surface if the device operates below strong inversion. $V_F < V_S < 2V_F$

surface potential



⇒ Experimentally we observe that the Drain current below threshold "subthreshold current" is independent of the Drain voltage V_D

⇒ This means that the subthreshold current is caused by diffusion rather than Drift.

After a lot of calculations, we get

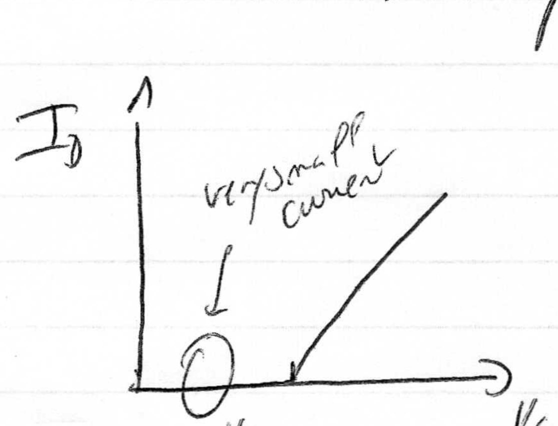
$$I_D = \mu_n \frac{W}{L} q \left(\frac{k_B T}{q}\right)^2 \frac{n_i^2}{N_a}\left[1-\exp\left(-\frac{qV_D}{k_B T}\right)\right]\frac{\exp\left(q\frac{V_s}{k_B T}\right)}{\mathcal{E}_s}$$

electric field at the surface $\mathcal{E}_s = -\frac{dV_s}{dx}$

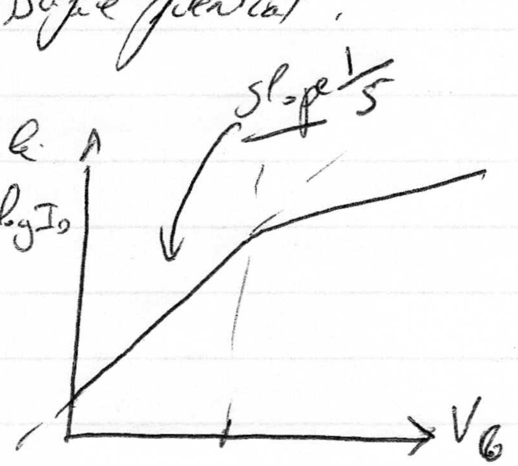
$$\mathcal{E}_s = \frac{qN_A}{C_D}$$

⇒ I_D is independent of V_D as long as V_D is larger than a few $\frac{k_B T}{q}$ (exponential term goes to zero).

⇒ I_D also increases exp. with the surface potential.



in log scale →



$$\boxed{S = \frac{k_B T}{q}\ln(10)\left(1+\frac{C_D}{C_{ox}}\right)}$$