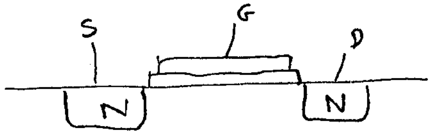
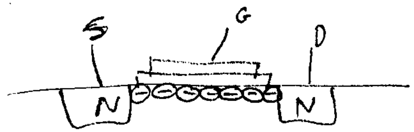
MOSFETS — a little deeper (Chapter 4)

Recall ---- N-channel MOSFET (4.1)



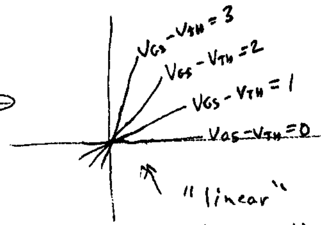
No conduction D-S with $V_{DS} = 0$



Positive voltage on gate causes formation of channel — Now current can flow.

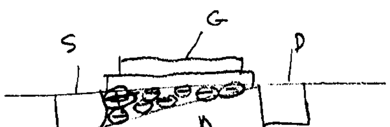
$V_S \approx V_D$

Looks like a variable resistor. ⟶



"linear" or "triode" region

As V_{DS} is increased ...



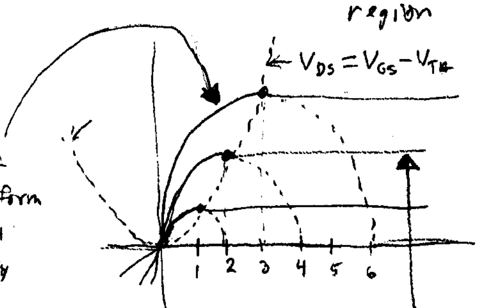
$V_D > V_S$

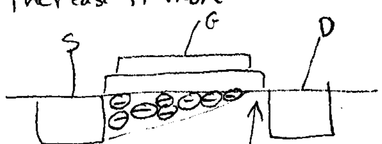
$V_{GS} - V_{TH} > 0$

$V_{GD} - V_{TH} > 0$, $V_{GS} - V_{TH} > V_{DS} - V_{TH}$ significantly

accumulation of charges isn't uniform

increase it more --





pinch off region

⟶ "saturation" region

$V_{GS} - V_{TH} > 0$ ← This part conducts

$V_{GD} - V_{TH} < 0$ ← "pinched off"

Formulas --- (As written in Hambley, Guru, etc---)

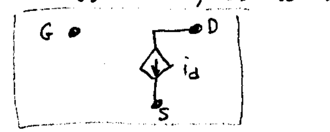
$$i_D = \begin{cases} 0 & V_{GS}-V_{TH} < 0 \\ K\left(2(V_{GS}-V_{TH})V_{DS} - V_{DS}^2\right) & V_{GS}-V_{TH} > 0,\ V_{DS} < V_{GS}-V_{TH} \\ K\,(V_{GS}-V_{TH})^2 & V_{GS}-V_{TH} > 0,\ V_{DS} > V_{GS}-V_{TH} \end{cases}$$

↑

$K = \frac{1}{2} K' \frac{W}{L}$ $\qquad \frac{\text{Amps}}{\text{Volts}^2}$

Usually $\underline{K'}$ is specified -- "process transconductance parameter"

$$i_D = \begin{cases} 0 & V_{GS}-V_{TH} < 0 \\ K'\frac{W}{L}\left((V_{GS}-V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right) & V_{GS}-V_{TH} > 0,\ V_{DS} < V_{GS}-V_{TH} \\ \frac{1}{2}K'\frac{W}{L}(V_{GS}-V_{TH})^2 & \end{cases}$$



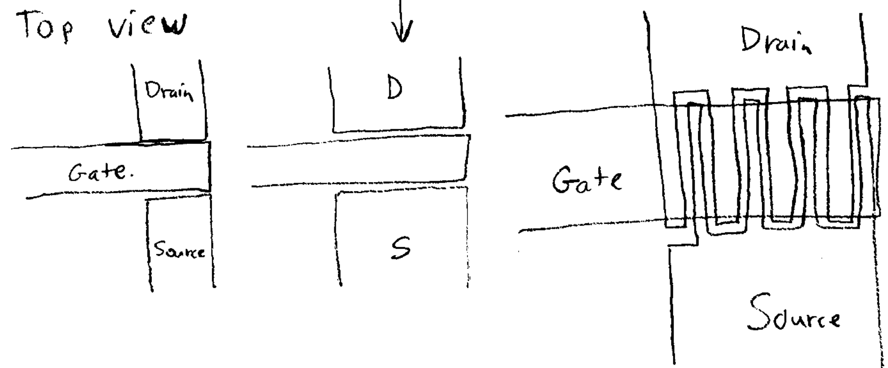
W = width of gate — usually around 1 μm (micron).

L = length of gate

usually W > L

sometimes W >> L

Top view



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Determining K' ..

$K' = \mu_n C_{ox}$

C_{ox} ← Capacitance, gate to channel

μ_n ← "surface mobility" ≡ mobility of carriers in the channel.

$C_{ox} = \dfrac{\varepsilon_{ox}}{t_{ox}}$

ε_{ox} ← permittivity of the insulator $= 3.45 \times 10^{-11}\ \frac{\text{Farad}}{\text{meter}}$ for SiO_2

t_{ox} ← Thickness of the insulator

→ so K depends on: Thickness of insulator
Width
Length.

μ_n is sometimes called μ_0.

Spice name UO or U0 — units = $\frac{cm^2}{\text{Volt}\cdot\text{sec}}$.

(UO: Letter O, U0: number zero)

Typical value $= 600\ \frac{cm^2}{V\cdot s} = 600 \times 10^{-4}\ \frac{m^2}{\text{volt}\cdot\text{sec}}$

Example: $\mu_n = 600$

$t_{ox} = 10^{-8}$ meter (.01 μm)

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \ \frac{3.45\times10^{-11}}{10^{-8}} = 3.45 \times 10^{-3}\ \frac{F}{m^2}$

What is K'?

$K' = \mu_n C_{ox} =$

$= \left(600\times10^{-4}\ \frac{m^2}{\text{volt sec}}\right)\left(3.45\times10^{-3}\ \frac{F}{m^2}\right)$

$= 2.07\times10^{-4}\ \frac{F}{\text{volt sec}} = \frac{\text{amps}}{\text{Volt}^2}$

Units:

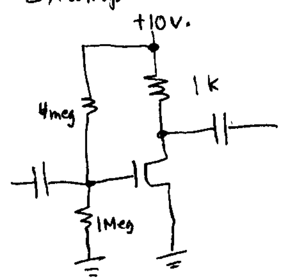
Farad $= \frac{\text{Coulomb}}{\text{Volt}}$

Amps $= \frac{\text{Coulombs}}{\text{Sec.}}$

$\frac{F}{\text{Volt Sec}} = \frac{\frac{\text{Coul}}{\text{Volt}}}{\text{Volt sec}} = \frac{\text{Coul}}{\text{Volt}^2\ \text{Sec}} = \frac{\text{Amps}}{\text{Volt}^2}$

1B 4

Example:



$\mu_n = 600\ \frac{cm^2}{Vs} = 6\times10^{-2}\ \frac{m^2}{Vs}$

$t_{ox} = .01\ \mu m = 10^{-8}\ m$

$W = 1\ \mu m$

$L = 10\ \mu m$ $\qquad V_{TH} = 0$

$K' = 2.07\times10^{-4} \approx 2\times10^{-4}$

$K'\frac{W}{L} = 2\times10^{-3}$

$V_{GS} = 0 \Rightarrow V_{GS} - V_{TH} = 2$

$I_D = \frac{1}{2}K'\frac{W}{L}(V_{GS}-V_{TH})^2$

$= \left(\frac{1}{2}\right)(2\times10^{-3})(2)^2$

$= 4\times10^{-3}$ Amps

For $R_D = 1K$, $V_R = 4 \Rightarrow V_D = V_{cc} - V_D$

$= 10 - 4$

$= 6$

$\boxed{\begin{array}{l} V_{DS} = 6 \\ I_D = 4\text{ma} \end{array}}$

Gain = ? –

$g_m = \frac{dI_{out}}{dV_{in}}$

$g_m = 2K(V_{GS}-V_{TH}) = 2\sqrt{K I_{DQ}}$

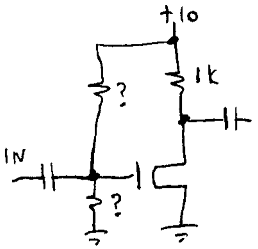
$= K'\frac{W}{L}(V_{GS}-V_{TH}) = \sqrt{2K'\frac{W}{L}I_{DQ}}$

$= (2\times10^{-3})(2) \qquad = \sqrt{2(2\times10^{-3})(4\times10^{-3})}$

$= 4\times10^{-3}$

$\frac{V_{out}}{V_{in}} = -g_m R_L = -(4\times10^{-3})(10^3) = -4$

"Design" for gain = −10, $R_D = 1K$



Same process as before:

$$\frac{V_{out}}{V_{in}} = -g_m R_L$$

$$-10 = -g_m (1000)$$

$$g_m = \frac{10}{1000} = .01 = 1 \times 10^{-2}$$

From before, $K' = 2 \times 10^{-4}$

Choose $V_{DS} = 5$ (half of supply)

This means $I_D = 5$ ma $= 5 \times 10^{-3}$ Amps.

$$g_m = \sqrt{2K'\frac{W}{L} I_{DQ}}$$

$$1 \times 10^{-2} = \sqrt{(2)(2 \times 10^{-4})\frac{W}{L}(5 \times 10^{-3})}$$

$$1 \times 10^{-4} = (2)(2 \times 10^{-4})\frac{W}{L}(5 \times 10^{-3})$$

$$\frac{1 \times 10^{-4}}{2 \times 10^{-6}} = \frac{W}{L}$$

$$50 = \frac{W}{L} \Rightarrow \begin{array}{l} L = 1\mu \\ W = 50\mu \end{array}$$

← L - usually choose the minimum. Sometimes increase to increase power capability.

$$K'\frac{W}{L} = (2 \times 10^{-4})\frac{50}{1}$$

$$= 10^{-2}$$

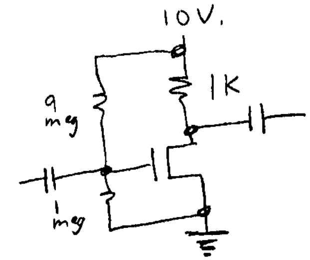
To set bias...

$$I_D = \frac{1}{2}K'\frac{W}{L}(V_{GS} - V_{TH})^2$$

$$5 \times 10^{-3} = \frac{1}{2}(10^{-2})(V_{GS} - V_{TH})^2$$

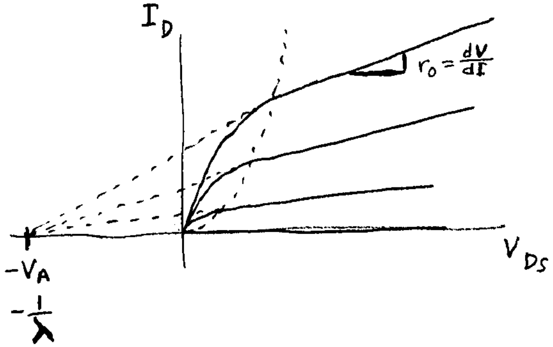
$$\frac{5 \times 10^{-3}}{.5 \times 10^{-2}} = (V_{GS} - V_{TH})^2$$

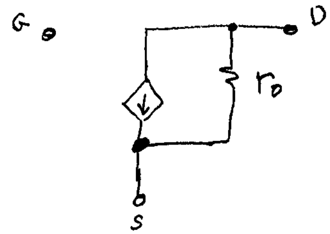
$$= 1 \text{ volt.}$$



"Channel length modulation"

Better equivalent circuit:





added term.

$$i_D = \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2 \underbrace{(1 + \lambda V_{DS})}$$

$$\downarrow$$

$$i_d = \underbrace{\frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2}_{\text{the current source}} + \underbrace{\frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2 \lambda V_{DS}}_{r_o}$$

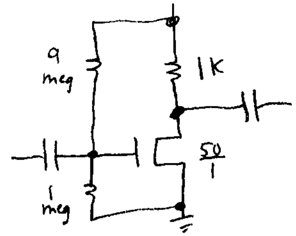
call this I_D (uppercase I)

$$\frac{1}{r_o} = \frac{i}{V_{ds}} = \lambda \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2$$

$$i_D = I_D (1 + \lambda V_{DS}) \qquad r_o = \frac{1}{\lambda I_D}$$

I_D = not counting channel length modulation.

Example --



Suppose $V_A = 100$
$\lambda = .01$

What is the gain now?

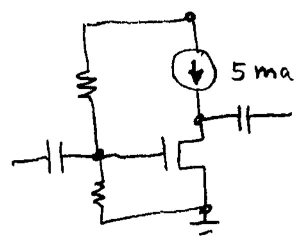
$$I_D = 5\text{ ma}$$

$$r_o = \frac{1}{\lambda I_D} = \frac{1}{(.01)(.005)} = 20K \quad (2 \times 10^4)$$

Effective $R_{LOAD} = 1K \| 20K = 952\ \Omega$

$$\text{Gain} = -g_m R_L = -(1 \times 10^{-2})(952) = -9.52$$

Example ---- (substitute current source for R_D)



$g_m = 1 \times 10^{-2}$ (as before)

gain $= -g_m R_L$ ← what is R_L?

$$R_L = r_o = \frac{1}{\lambda I_D} = \frac{1}{(.01)(.005)} = 20K$$

$$\text{gain} = -g_m R_L = -(1 \times 10^{-2})(2 \times 10^4) = -200$$

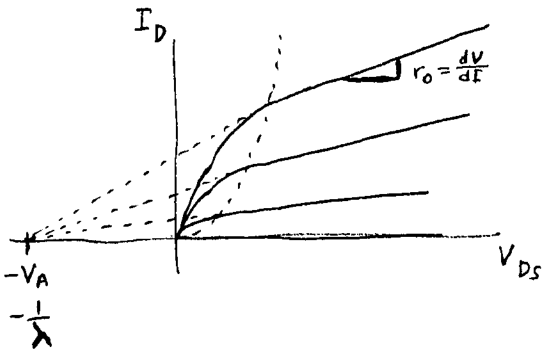
⇒ We can get decent gain from FETs with no load!

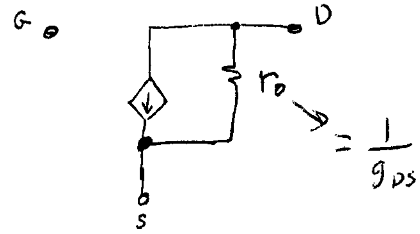
Spice: V_{TH} = "VTO" ← Letter O. λ = "lambda"

"Channel length modulation"

(1B 7)

Better equivalent circuit:





added term.

$$i_D = \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2 \overbrace{(1 + \lambda V_{DS})}$$

$$\downarrow$$

$$i_D = \underbrace{\frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2}_{\text{the current source}} + \underbrace{\frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2 \lambda V_{DS}}_{r_o}$$

the current source ↑ call this I_D (uppercase I)

r_o ↓

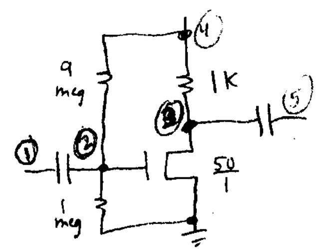
$$\frac{1}{r_o} = \frac{i}{V_{ds}} = \lambda \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2$$

$i_D = I_D (1 + \lambda V_{DS})$ $r_o = \frac{1}{\lambda I_D}$

I_D = not counting channel length modulation.

Example --

(1B 8)



Suppose $V_A = 100$
$\lambda = .01$

What is the gain now?

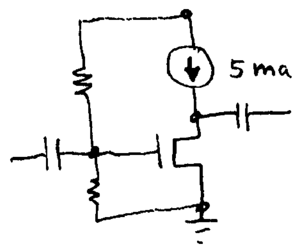
$I_D = 5$ ma $I_D = 5.24$ ma ↑ why?

$r_o = \frac{1}{\lambda I_D} = \frac{1}{(.01)(.005)} = 20K$ (2×10^4)

Effective $R_{LOAD} = 1K \| 20K = 952\ \Omega$

Gain $= -g_m R_L = -(1 \times 10^{-2})(952) = -9.52$ 9.97

Example --- (substitute current source for R_D)



$g_m = 1 \times 10^{-2}$ (as before)

gain $= -g_m R_L$ ← what is R_L?

$R_L = r_o = \frac{1}{\lambda I_D} = \frac{1}{(.01)(.005)} = 20K$

gain $= -g_m R_L = -(1 \times 10^{-2})(2 \times 10^4) = -200.$ 212

⇒ We can get decent gain from FETs with no load!

bias -- $V_D = .9$? ← because of r_o