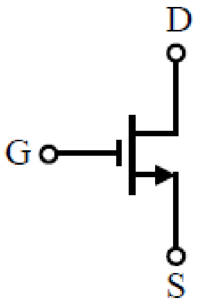
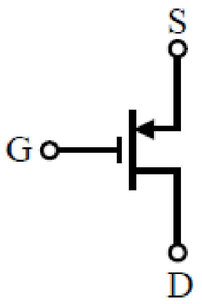
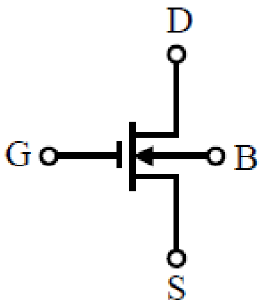
MOS Symbol:



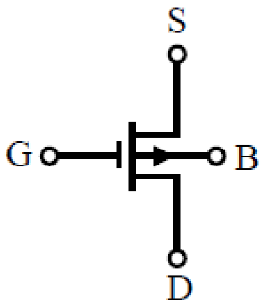
Enhancement NMOS with $V_{BS} = 0V$.



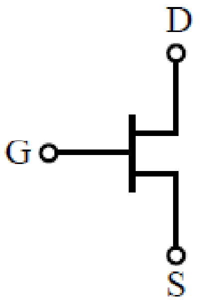
Enhancement PMOS with $V_{BS} = 0V$.



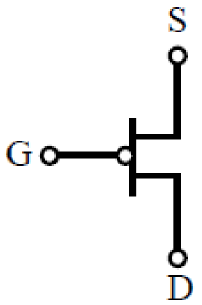
Enhancement NMOS with $V_{BS} \neq 0V$.



Enhancement PMOS with $V_{BS} \neq 0V$.

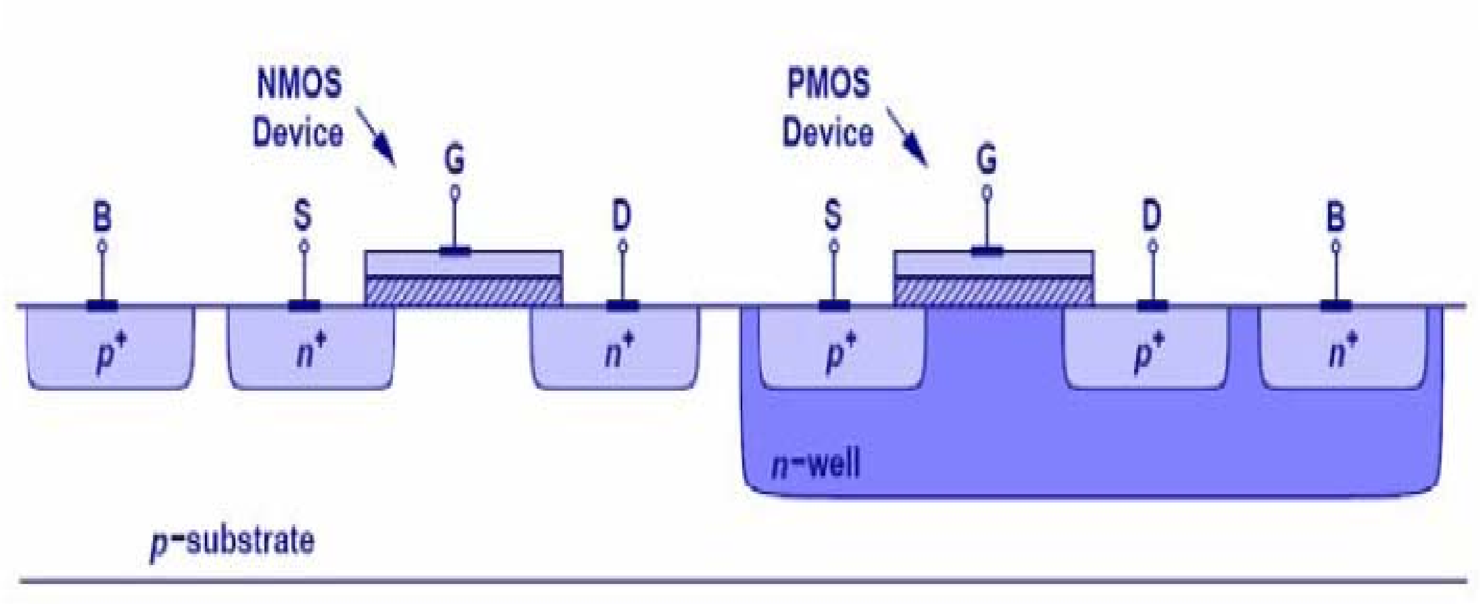


Simple NMOS symbol



Simple PMOS symbol

CMOS Process:



Simple MOS Large-Signal Model:

3 regions of operation:

Cutoff Region:

$i_D = 0,\ V_{GS} - V_{TH} < 0$ (ignores subthreshold current)

Linear, Triode, or Non-saturation Region:

$$i_D = \frac{\mu_o C_{ox} W}{L}\left[(V_{GS} - V_{TH}) - \left(\frac{V_{DS}}{2}\right)\right] V_{DS}\ ,\ 0 < V_{DS} < V_{GS} - V_{TH}$$

Active or Saturation Region:

$$i_D = \frac{\mu_o C_{ox} W}{2L}(V_{GS} - V_{TH})^2\ ,\ 0 < V_{GS} - V_{TH} < V_{DS}$$

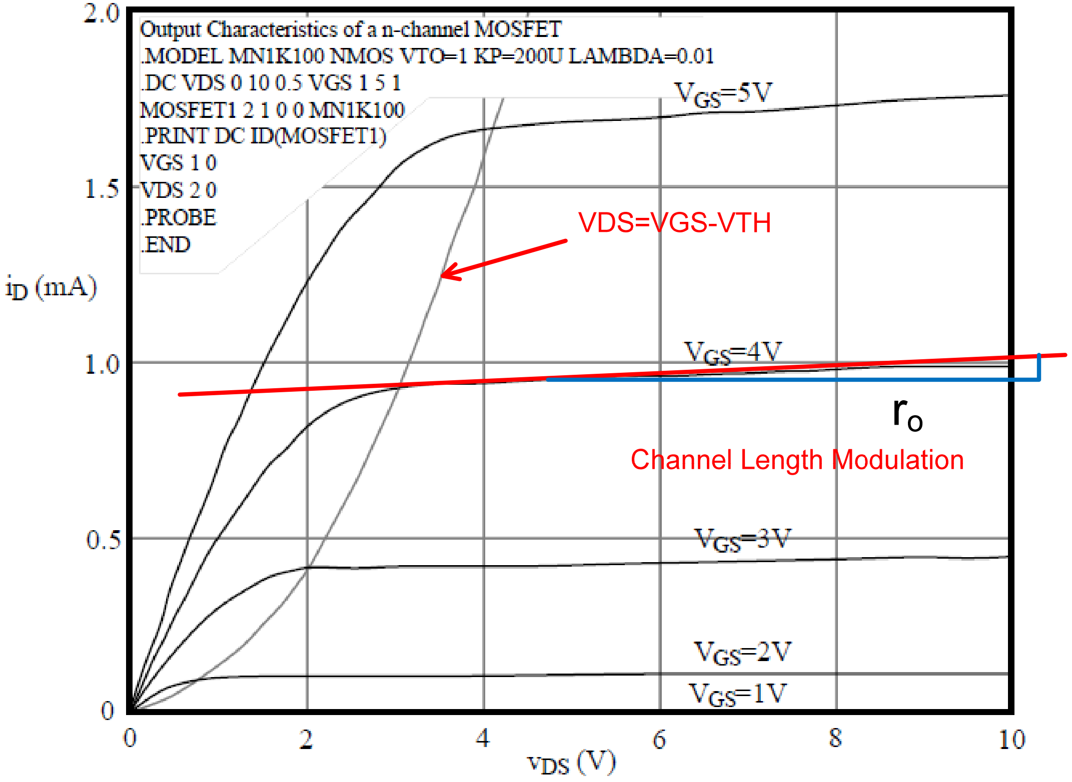
μ_o = surface mobility of the channel for the n-channel or p-channel device (cm^2/Volt.Sec)

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$ = capacitance per unit area of the gate oxide (F/cm^2)

ε_{ox}= permittivity of SiO2 =3.9*8.854e-14 (F/cm)

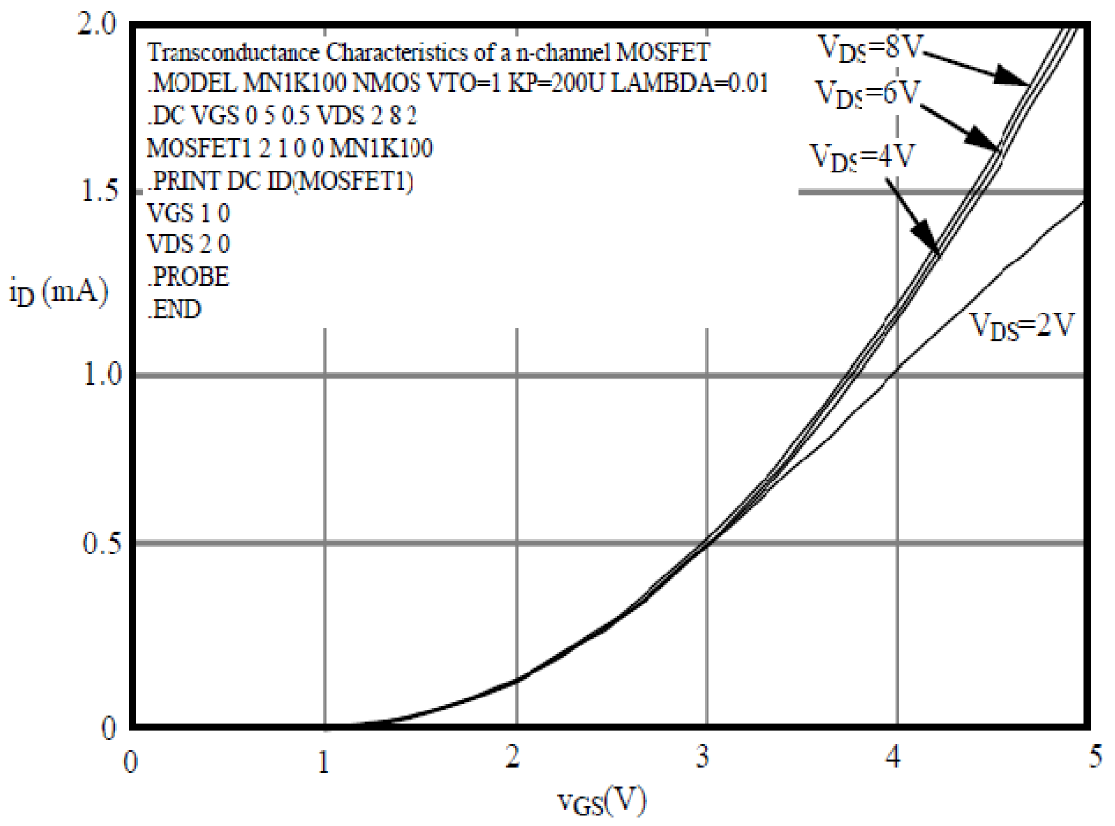
t_{ox} =oxide thickness

Output Characteristic of NMOS:



VGS=1V, MOS in cut-off region.

Transconductance Characteristic of NMOS:

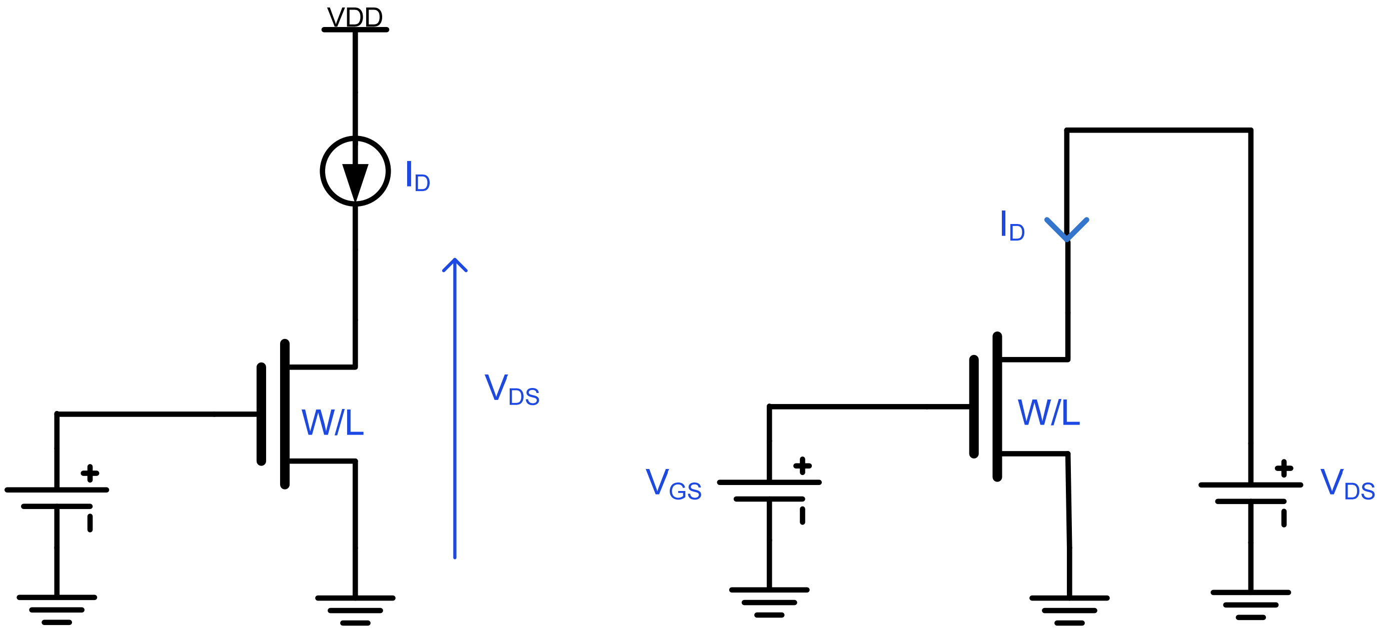


Transconductance Characteristics of a n-channel MOSFET

```
.MODEL MN1K100 NMOS VTO=1 KP=200U LAMBDA=0.01
.DC VGS 0 5 0.5 VDS 2 8 2
MOSFET1 2 1 0 0 MN1K100
.PRINT DC ID(MOSFET1)
VGS 1 0
VDS 2 0
.PROBE
.END
```

The gm is lower at VDS=2.

Control of Operating Region:

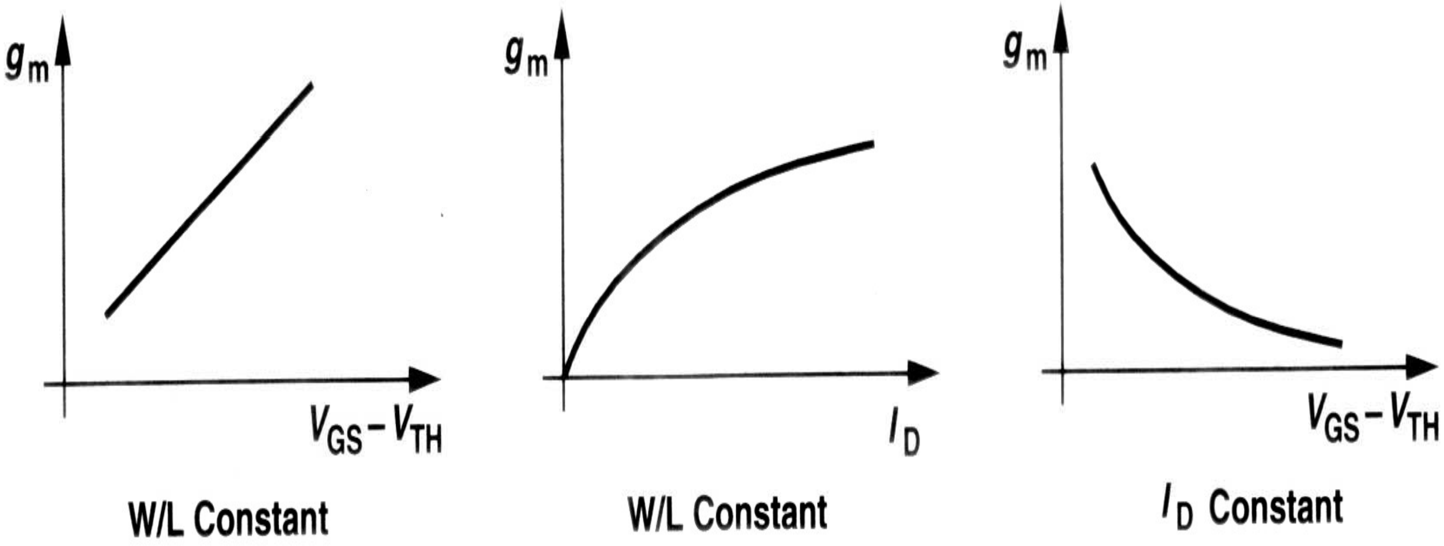


Using VGS and ID or using VGS and VDS

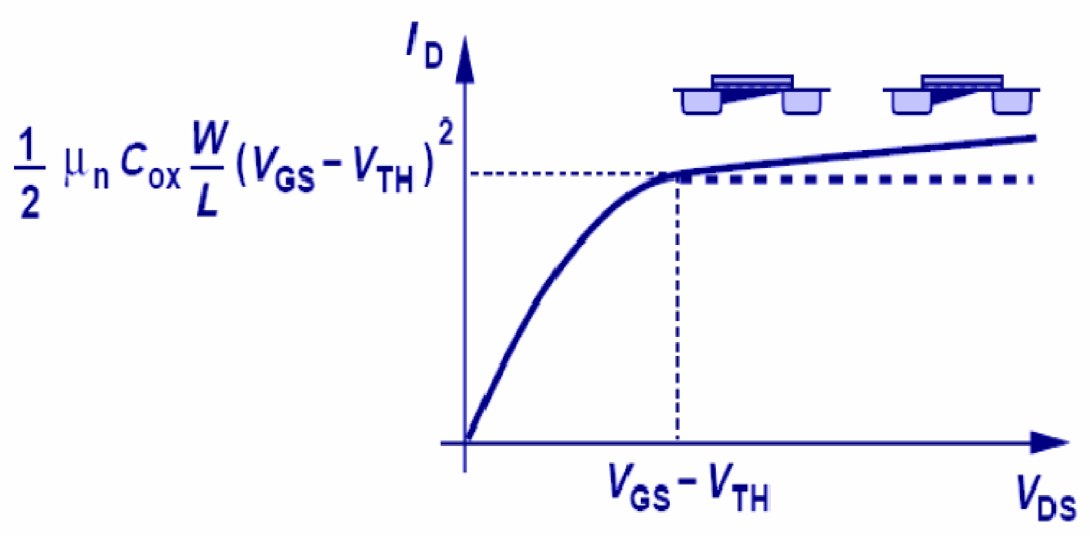
Gm:

In active region, $I_D = \frac{1}{2}\mu_o C_{ox}\frac{W}{L}{V_{OV}}^2$			
$g_m = \frac{\partial I_D}{\partial V_{GS}}$	$\mu_o C_{ox}\frac{W}{L}V_{OV}$	$\sqrt{2\mu_o C_{ox}\frac{W}{L}I_D}$	$\frac{2I_D}{V_{OV}}$
g_m ↑	$\frac{W}{L}$↑, V_{OV} const, I_D↑ $\frac{W}{L}$ const, V_{OV} ↑, ${I_D}^2$↑	$\sqrt{\frac{W}{L}}$ ↑, I_D const, V_{OV}↓ $\frac{W}{L}$ const, $\sqrt{I_D}$ ↑, V_{OV}↑	I_D↑, V_{OV} const, $\frac{W}{L}$↑ I_D const, V_{OV} ↓, $\sqrt{\frac{W}{L}}$↑
	Maintain V_{OV}, increase size and I_D Maintain size, increase overdrive and ID Maintain I_D, increase size and reduce overdrive → Towards sub-threshold region		

Gm:


g_m
$V_{GS} - V_{TH}$
W/L Constant
g_m
I_D
W/L Constant
g_m
$V_{GS} - V_{TH}$
I_D Constant

Channel Length Modulation:



The current equation for Saturation Region is a constant since it is independent of V_{ds}. This is not true in reality. I_D in saturation region is a weak function of drain voltage.

As $V_{DS}\uparrow$, the effective channel-length, L′ ,decrease.

Channel Length Modulation:

$$\frac{1}{L'} = \frac{1}{L-\Delta L} = \frac{1}{L}\left(1 + \frac{\Delta L}{L}\right) = \frac{1}{L}(1 + \lambda V_{DS})$$

$$\lambda \propto \frac{1}{\mathrm{L}}$$

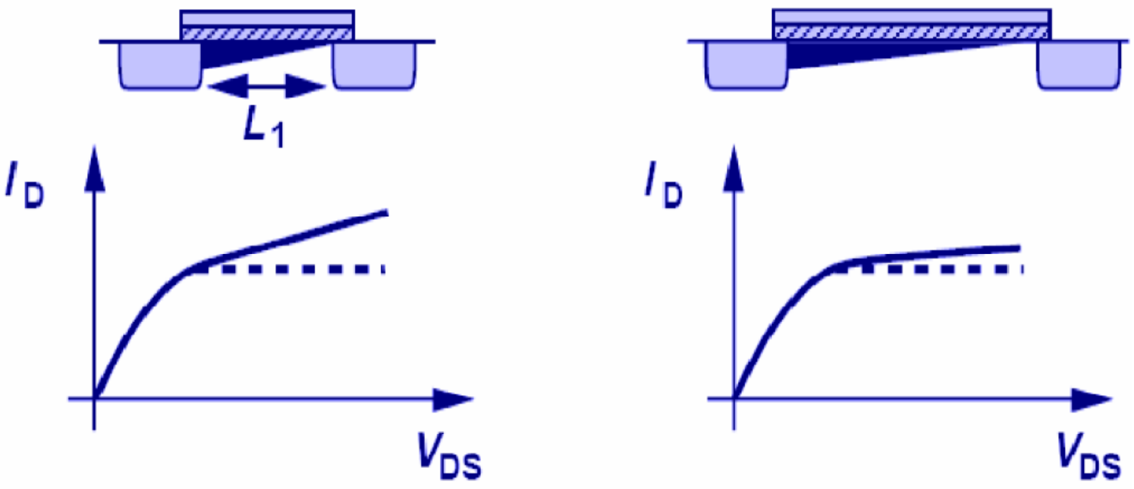
λ : Channel-length modulation coefficient. It represents the relative variation in length for a given increment in VDS.

With Channel-length Modulation:

$$I_D = \frac{\mu_o C_{ox} W}{2L'}(V_{GS} - V_{TH})^2 = \frac{\mu_o C_{ox} W}{2L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

$$g_m = \mu_o C_{ox}\frac{W}{L}V_{OV}(1 + \lambda V_{DS}) = \sqrt{2\mu_o C_{ox}\frac{W}{L}I_D(1 + \lambda V_{DS})} = \frac{2I_D}{V_{OV}}$$

λ and L:

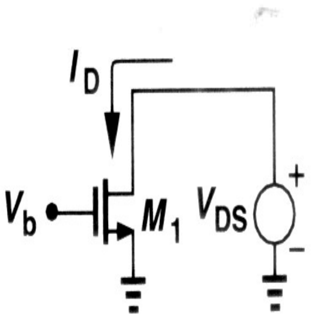


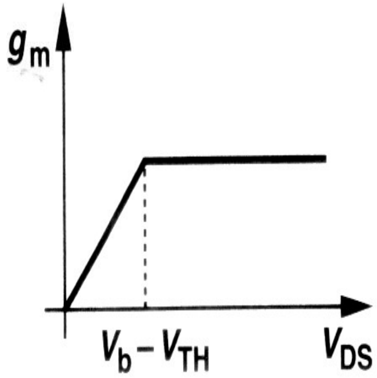
$$I_D = \frac{\mu_o C_{ox} W}{2L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

$$\frac{\partial I_D}{\partial V_{DS}} = \frac{\mu_o C_{ox} W}{2L}(V_{GS} - V_{TH})^2 \lambda \propto \frac{\lambda}{\mathrm{L}} \propto \frac{1}{\mathrm{L}^2}, \text{ since } \lambda \propto \frac{1}{\mathrm{L}}$$

- Less channel-length modulation effect for longer L.
- If the L is doubled, the slope reduces by 4X.
- Using long L for higher ro.

Triode Region:



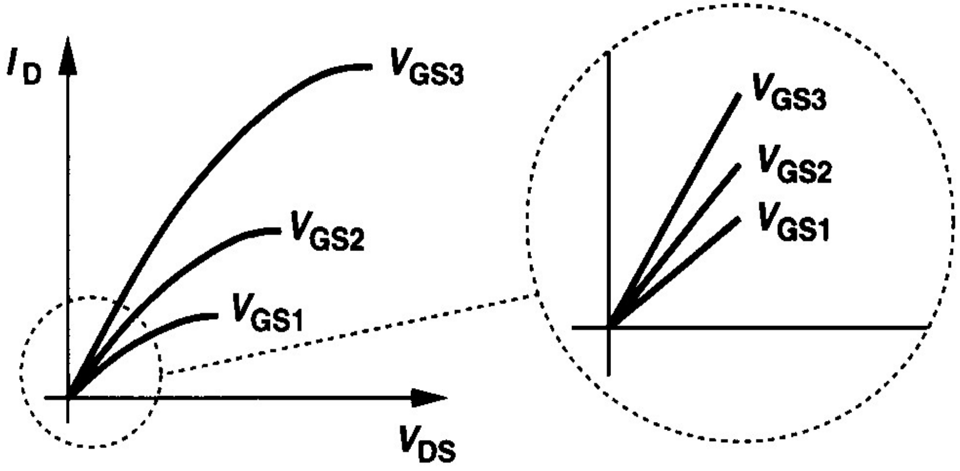


As $V_{DS} \geq V_b - V_{TH}$, M1 is in saturation. I_D and g_m is relatively constant.
As $V_{DS} \geq V_b - V_{TH}$, M1 enter triode region and:

$$g_m = \frac{\partial}{\partial V_{GS}} \left\{ \frac{\mu_o C_{ox} W}{L} \left[(V_{GS} - V_{TH}) - \left(\frac{V_{DS}}{2} \right) \right] V_{DS} \right\} = \mu_o C_{ox} \frac{W}{L} V_{DS}$$

In triode region, as V_{DS}↓, g_m↓. No gain in triode region.

Triode Region: Ron



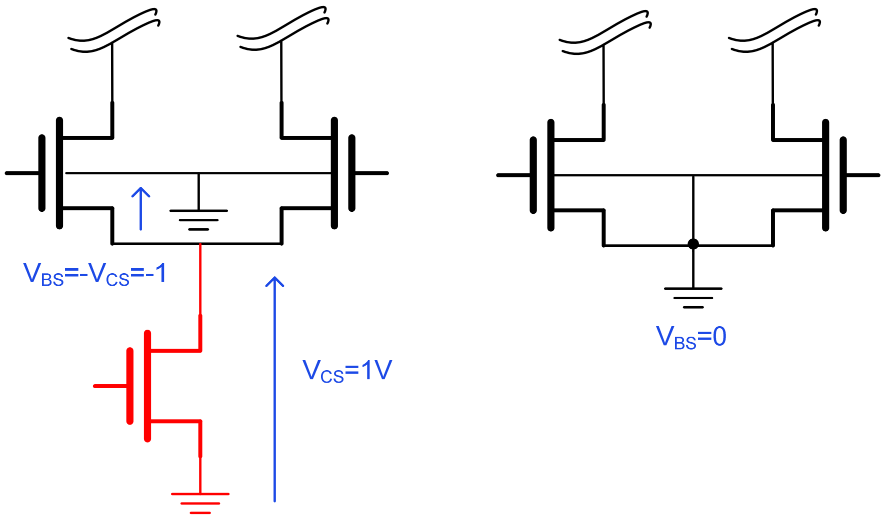
In triode region, if $V_{DS} << V_{GS} - V_{TH}$

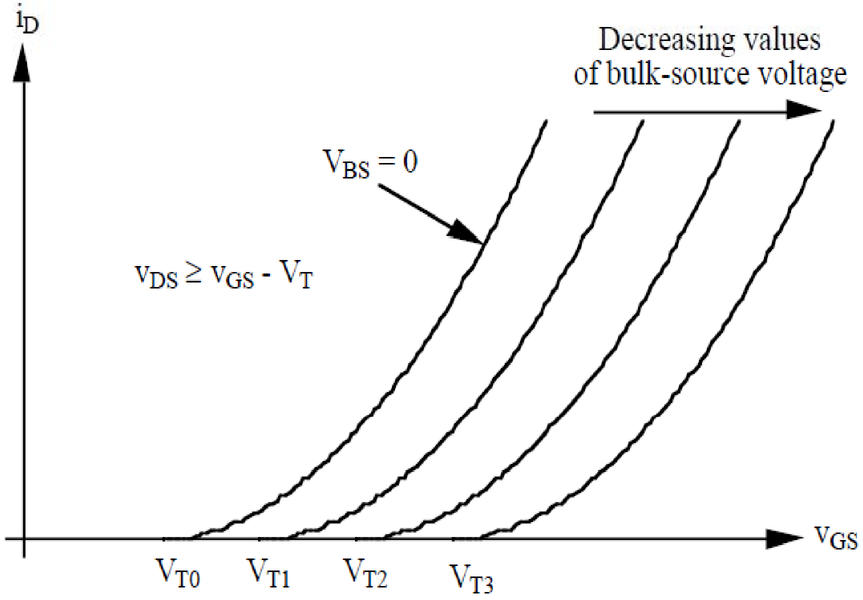
$$I_D = \frac{\mu_o C_{ox} W}{L}\left[(V_{GS} - V_{TH}) - \left(\frac{V_{DS}}{2}\right)\right] V_{DS} \approx \mu_o C_{ox} \frac{W}{L}(V_{GS} - V_{TH}) V_{DS}$$

$$R_{ON} = \frac{1}{\mu_o C_{ox} \frac{W}{L}(V_{GS} - V_{TH})}$$

To reduce R_{ON}, increase the size or increase the overdrive voltage.

Effect of Back Gate:





With $V_{BS}<0$, more difficult to turn on the NMOS.

With $V_{BS}>0$, easier to turn on the NMOS.

Threshold Voltage, V_{TH}:

Zero bias (V_{BS}=0) threshold voltage: $V_{TH0} = \Phi_{MS} + 2\Phi_F + \frac{Q_{dep}}{C_{ox}}$

Φ_{MS}= difference between work functions of the polysilicon gate
and the silicon substrate

Φ_F = strong inversion surface potential (V)

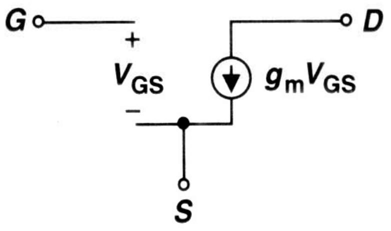
Q_{dep}= charge in depletion region

Threshold voltage:

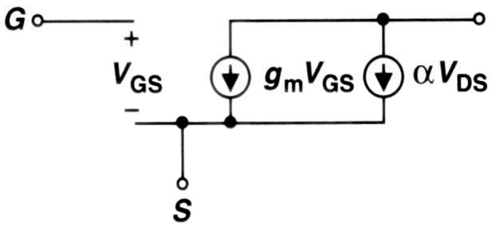
$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|}\right)$$

γ = body effect coefficient

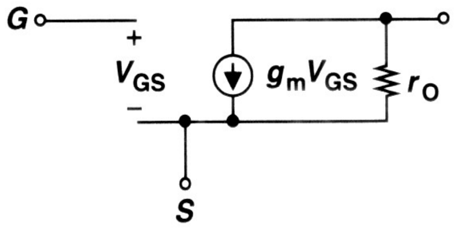
Small Signal Model:



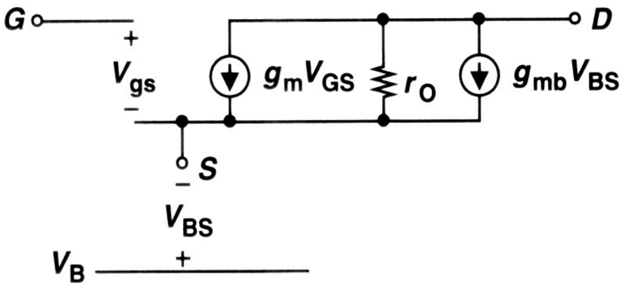
(a)



(b)



(c)



(d)

Small Signal Model:

An approximation of the large-signal model around the operating point (DC-bias).
Channel length modulation → I_D varies with V_{DS} → Resistor.

$$r_o = \frac{1}{\partial I_D / \partial V_{DS}} = \frac{1}{\frac{\mu_o C_{ox} W}{2L}(V_{GS} - V_{TH})^2 \lambda} \approx \frac{1}{\lambda I_D}$$

R_o, the output impedance will limits the voltage gain of amplifier.
$G_m.r_o$ is called intrinsic gain of the transistor.

Bulk potential affects threshold voltage and hence the GS overdrive voltage.

$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} = \mu_o C_{ox} \frac{W}{L}(V_{GS} - V_{TH})\left(-\frac{\partial V_{TH}}{\partial V_{BS}}\right) = g_m \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}} = \eta g_m$$

$g_m V_{GS}$ and $g_{mb} V_{SB}$ have the same polarity.
Raising the gate voltage has the same effect as raising the bulk potential.

Complete MOS Small-signal Model: