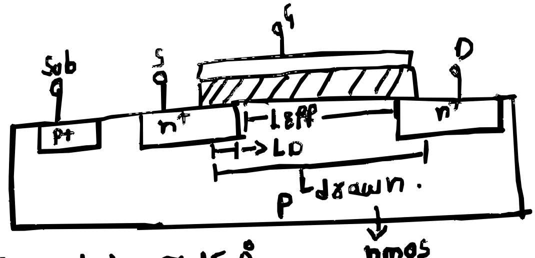
Analog Electronics

-> the level of abstraction of knowlage required to study analog design is Quantum physics -> Solid state physics -> Semiconductor device physics -> device modelling -> design of circults.

Mosfet as a switch

-> if gate of n-mos is high -> the resistance R_{DS} is low it conducts Electricity

-> If gate of n-mos is low -> the resistance R_{DS} is high it act as open circuit

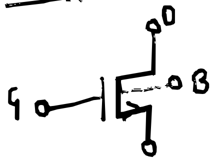


Mosfet structure

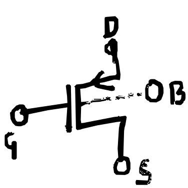
$L_{drawn} - 2L_D = L_{eff}$

* typical value for $L_{eff} \approx 10\,nm$ & $t_{ox} \approx 15\,Å$
* mosfet is symetrical device
* the substrate should be reverse biased with respet to source & Drain to prevent latch up
* Pmos is created by negating all the doping types
* Pmos is fabricated in an N-well & substrate is connected to highest Potential (V_{DD})

Mosfet symbol



Nmos

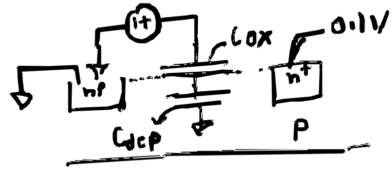


Pmos

Mosfet V-I characteristics

→ Threshold Voltage (V_{Th})

* As V_g becomes more +ve the holes in the substrate [nmos] get repelled from the gate hence the depletion region is formed
* Increase V_g increase the width of the depletion region.



* the channel can be modeled as two cap connected in series with voltage divider
* the value of V_g the inversion of channel occurs is called V_{TH}
* if the value of V_g is increased further the charge in depletion region remain constant. while the channel charge density continious to increase. which increase I_D

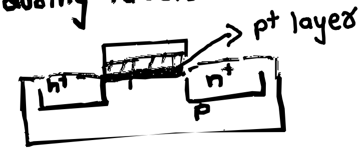
$$* \quad V_{TH} = \phi_{MS} + 2\phi_F + \frac{Q_{dep}}{C_{ox}}$$

ϕ_{MS} → difference between workfunction of polysilican 4 silicon substrate.

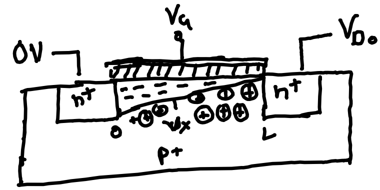
$\phi_F \rightarrow \frac{KT}{q} \ln\left(N_{sub}/n_i\right)$ → K → Boltzmann constant
N_{sub} → doping density of substrate.

$\phi_{dep} \rightarrow \sqrt{4q\epsilon_{si}|\phi_F|N_{sub}}$ $\quad \epsilon_{si}$ → dielectric constant of Si

* the V_{Th} of the mosfet is adjusted by adding dopent to the channel area during fabaication



I-V characteristics of Mosfet



* the charge per unit length in mosfet is given

$$Q_d(x) = \cdot\, C_{ox} W \left(V_{GS} - V_x - V_t\right)$$

where $C_{ox} = \varepsilon_o / t_{ox}$

* $I_d = Q_d \times V$ where $V \rightarrow$ Velocity of electron.

$$\therefore I_d = C_{ox} W \left(V_{GS} - V_x - V_t\right) V$$

we know that $V = u E$ & $E = -\frac{dV}{dx}$

$$\therefore I_d = C_{ox} W \left(V_{GS} - V_x - V_t\right) u \frac{dV}{dx}.$$

$$\int_0^L I_d \, dx = \int_0^{V_{DS}} C_{ox} W \left(V_{GS} - V_x - V_t\right) u \, dV.$$

* the current in the channel is constant

$$\therefore I_d = C_{ox} \frac{W}{L} u \left[\left(V_{GS} - V_t\right) V_{DS} - \frac{V_{DS}^2}{2}\right]$$

* the peak current is when $V_{DS} = V_{GS} - V_t \Rightarrow C_{ox} \frac{W}{L} u \left[\left(V_{GS} - V_t\right) \frac{V_{DS}^2}{2}\right]$

* we call $V_{GS} - V_{Th}$ as overdrive voltage.
* $W/L \rightarrow$ aspect ratio
* $V_{DS} \leq V_{GS} - V_{Th} \rightarrow$ triode region.
* If $V_{DS} \leq V_{GS} - V_{Th}$ then $I_d \approx C_{ox} \frac{W}{L} u_o \left[V_{GS} - V_t\right] V_{DS}$

& $R_{on} = \dfrac{1}{C_{ox} \frac{W}{L} u_o \left[V_{GS} - V_t\right]} \rightarrow$ Voltage controlled resistor

* the current becomes constant when $V_{DS} \geq V_{GS} - V_{Th}$ this region is called saturated region. and the channel becomes pinched off. there will be current in the region after pinched off. due to the increase of velocity of electron in the pinched point. electron simply shoot to the drain of the device

-> Ideal amplifier $y(t) = a_0 + a_1 x(t)$

-> real amplifier $y(t) = a_0 + a_1 x(t) + a_2 x^2(t)$ ......

↳ cause distortion

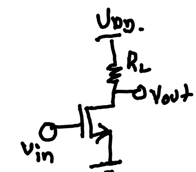
-> Performance parameter :-

- ↳ Speed
- gain
- -> output swing
- ↳ linearity
- ↳ Noise
- Input output Impedence.
- ↳ power dissipation.
- ↳ Voltage supply

Amplifier categories

- common source stage
  - ↳ with resistor load
  - ↳ diode connect load
  - ↳ Current-source load
  - ↳ Active load
  - ↳ source degenerative
- source follower
  - ↳ resistive bias
  - ↳ Current-source bias
- common gate stage
  - ↳ resistive load
  - ↳ Current-source load
- cascode.
  - ↳ telescopic
  - ↳ Folded

* Common source with resistor load



-> $V_{out} = V_{DD} - R_L \times \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2$

-> Swing range (output). $= V_{DD} \rightarrow V_{in} - V_T$

-> Input swing $= 0 \rightarrow V_{in} - V_T$.

- for $V > V_{in} - V_T \Rightarrow$ mosfet is in triode region.

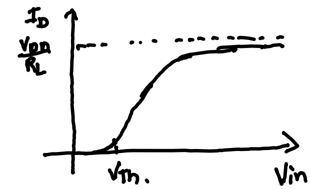
-> for triode region V_{out} is

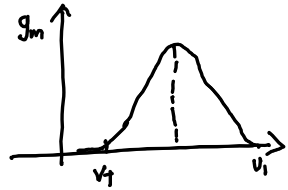
$$V_{out} = V_{DD} \times \frac{R_O}{R_L + R_O} = R_o \Rightarrow \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)$$

-> gain $A_V = \frac{\partial V_{out}}{\partial V_{in}} = -R_L \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T) \Rightarrow -g_m R_L$

-> g_m change when we apply large signal i.e g_m depend on V_{in}.

graph





$$\text{Gain} = -g_m R_D \Rightarrow -\sqrt{2 u_n C_{ox} \frac{W}{L} I_D} \times \frac{V_D}{I_D}$$

$V_D \rightarrow$ voltage acrooss resister

To increase gain Increase

- $\rightarrow W/L \rightarrow$ It lead to increase in device capacitance. & Increase V_D which reduce the output swing (due to reduce in R_D due to increase in ω].
- $\rightarrow V_D$ constant I_D reduce $\rightarrow$ Increase in R_D which lead to increase in output time constant.

$\Rightarrow$ the channel length modulation become signifent when we increase R_L.

$$V_{out} = V_{DD} - R_L \frac{K}{2}(V_{GS}-V_T)^2(1+\lambda V_{out}) \qquad K \rightarrow C_{ox} W/L\, u_o$$

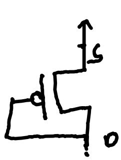
$$\frac{dV_{out}}{\partial V_{in}} = -R_L K (V_{GS}-V_T)(1+\lambda V_{out}) - R_L \frac{K}{2}(V_{GS}-V_T)^2 \lambda \frac{V_{out}}{V_{in}}.$$

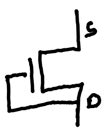
$$A_V = -R_L g_m - \frac{R_L}{r_o} A_V \qquad 1/r_o = K/2 (V_{GS}-V_T)^2 \lambda$$

$$A_V = -g_m \frac{R_L r_o}{R_L + r_o} \Rightarrow -g_m (R_L \| r_o)$$

$\rightarrow$ $1/g_m$ is Very less than r_o

$\rightarrow$ diode connected mosfet :- if drain is connected to gate.



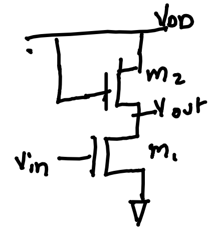


$\therefore$ output impedence $= 1/g_m \| r_o \approx 1/$

$$g_m V_x + \frac{V_x}{R} = I \Rightarrow \frac{I}{V_x} = g_m + \frac{1}{R_L} + g_{mb}$$

$$\Rightarrow \frac{1}{R_{eq}} = \frac{1}{r_m} + \frac{1}{R_L} + \frac{1}{r_{mb}}$$

→ If we neglect r_d since it is large the equivalent resistance in diode connect is $\approx 1/g_m + g_{mb}$



→ ∴ the gain of diode connect is $A_V = -g_m R_D$

$$= -g_{m_1} \times \frac{1}{g_{m_2} + g_{mb_2}}.$$

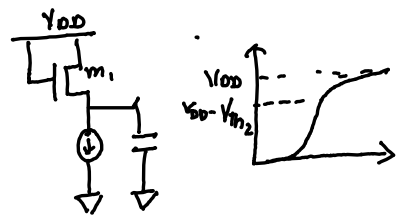
$$= \frac{-g_{m_1}}{g_{m_2}} \times \frac{1}{1 + \frac{g_{mb_2}}{g_{m_2}}} = -\frac{g_{m_1}}{g_{m_2}} \times \frac{1}{1+\eta} \quad \eta = \frac{g_{mb_2}}{g_{m_2}}.$$

$$\Rightarrow \frac{\sqrt{2 W_1/L_1 C_{ox} \mu_n I_{D_1}}}{\sqrt{2 W_2/L_2 C_{ox} \mu_n I_{D_2}}} \times \frac{1}{1+\eta} \qquad I_{D_1} = I$$

$$= \frac{\sqrt{W_1/L_1}}{\sqrt{W_2/L_2}} \times \frac{1}{1+\eta}.$$

→ If η is neglected bias is independent of bias current or Voltage therefore it is linear

→ if mosfet 1 is off I_D is zero the voltage will go to VDD. during this time it will reach. $V_{DD} - V_{Th_2}$ fast then transistor turns off then it will go to V_{DD} slowly due to reverse bias current. ∴ for high speed application we can consider it will reach $V_{DD} - V_{Th_2}$.

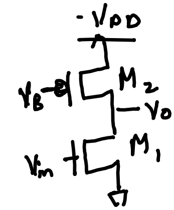


→ gain is weak function of dimention we need to rise $W_1/L_1 / W_2/L_2$ to 25 to get gain of 5.

→ In current technology channel length modulation is quite signifent which can't be ignored

$$\therefore A_V = g_{m_1} \times \left(1/g_{m_2} \| r_o \| r_o\right).$$

* common source with current source load.



→ $\text{gain} = -g_m(r_1 \| r_2)$.

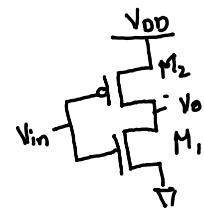
→ if r_2 is large $\text{Gain} = -g_m r_1$

→ swing range → $V_{min} = V_{in} - V_{Th}$ $V_{max} = V_B - V_T$.

→ $\text{gain} = -g_m r_1$

$$= -\sqrt{2 \times \frac{W}{L} u_o C_{ox} I_D} \times \frac{1}{\lambda I_D}$$

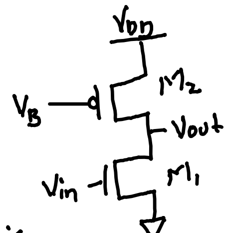
* common source with active load.



→ $A_V = -(g_{m1} + g_{m2})(r_{o1} \| r_{o2})$.

→ Issue with this configuration
↳ bias voltage are dependent on PVT. if there is mismatch it cause change in current.

* common source in triode region.



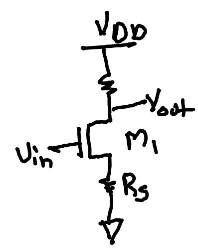
→ M_2 is in triode region.

→ $\text{gain} = -g_m(r_1 \| R_o)$

→ $R_o = \dfrac{1}{u_p C_{ox} \frac{W}{L}(V_{DD} - V_B - |V_T|)}$.

→ drawback → R depends on PVT like V_T, W/L, C_{ox} which is difficult to control & change with temperature.

* common source with degenerative load



→ gm is function of V_{GS} degenerative is used to make gain as weak function of Vin.

→ It make circuit gain more linear.

$$G_{m(new)} = \frac{d\, I_d}{d\, V_{in}} \Rightarrow \frac{\partial I_d}{\partial V_{GS}} \times \frac{\partial V_{GS}}{\partial V_{in}}.$$

$$V_{gs} = V_{in} - I_D R_S \Rightarrow \frac{\partial V_{gs}}{\partial V_{in}} = 1 - \frac{\partial I_D}{\partial V_{in}} R_S .$$

$$\Rightarrow \frac{\partial I_D}{\partial V_{gs}} \times \frac{\partial V_{gs}}{\partial V_{in}} = \frac{\partial I_D}{\partial V_{gs}} \left(1 - \frac{\partial I_D}{\partial V_{in}} R_S \right).$$

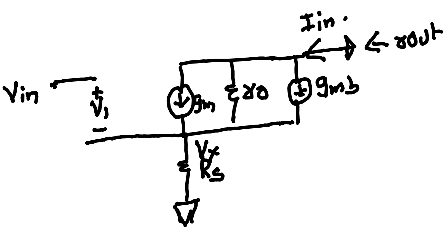
$$\Rightarrow G_{m(New)} = g_{m(old)} \left(1 - G_{m(new)} R_S \right).$$

after rearranging $G_{m(new)} = \dfrac{g_{m(old)}}{1 + g_{m(old)} R_S}$ → Neglecting body effect.

$\therefore$ small signal gain $A_V = -g_m R_D \Rightarrow -G_{m(New)} R_D$

$$\Rightarrow \frac{g_m \times R_D}{1 + g_m R_S}$$ → Neglecting body effect.

* if R_S is increased G_m become weak function of g_m & if $R_S \gg 1/g_m$.
  $G_m \approx 1/R_S$
* the drawback of this circuit is it reduce the gain of the circuit.
* with body effect gain changes to



$$I_{in} = g_m V_1 - g_{mb} V_x - \frac{I_{in} R_S}{r_o}$$

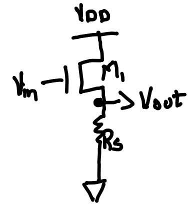
$$\frac{I_{in}}{V_{in}} \Rightarrow G_m = \frac{g_m r_o}{R_S + [1 + (g_m + g_{mb}) R_S] r_o}$$

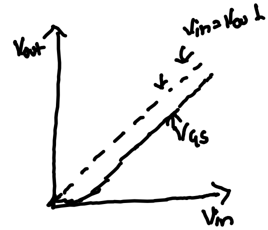
$\therefore A_V = -G_m R_D$

$r_{out} = R_S + [1 + (g_m + g_{mb}) R_S] r_o \quad \therefore R_{out} = r_{out} \| R_D$

$r_{out} \approx R_S + [(g_m + g_{mb}) R_S r_o \quad$ if $g_m g_{mb} R_S \gg 1$.

Source follower amplifier





→ It act as a Voltage buffer

→ $\frac{1}{2} u_o C_{ox} \frac{W}{L} \left(V_{in} - V_{out} - V_{Th}\right)^2 R_S = V_{out}$. ①

→ differensiating with respect to Vin

$$\frac{1}{2} u_o C_{ox} \frac{W}{L}\, 2\left[V_{in} - V_{out} - V_{Th}\right] R_S \left(1 - \frac{\partial V_{out}}{\partial V_{in}} - \frac{\partial V_{Th}}{\partial V_{in}}\right) = \frac{\partial V_{out}}{\partial V_{in}}$$

$$\Rightarrow \frac{\partial V_{Th}}{\partial V_{in}} \Rightarrow \frac{\partial V_{Th}}{\partial V_{SB}} \times \frac{\partial V_{SB}}{\partial V_{in}} \qquad V_{SB} = +V_{out} \qquad \frac{\partial V_{Th}}{\partial V_{SB}} = \eta$$

$$\Rightarrow \frac{dV_{out}}{\partial V_{in}} = A_V = \frac{u_o C_{ox} \frac{W}{L}\left(V_{in} - V_{Th} - V_{out}\right) R_S}{1 + u_n C_{ox} \frac{W}{L}\left(V_{in} - V_{Th} - V_{out}\right) R_S (1+\eta)}$$

$\Rightarrow g_m = u_n C_{ox} \frac{W}{L}\left(V_{in} - V_{Th} - V_{out}\right)$ → by differenmastion of 1.

$$A_V = \frac{g_m R_S}{1 + g_m R_S (1+\eta)}$$

$$A_V = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

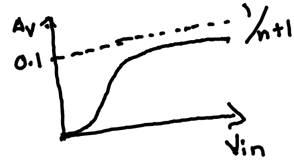
Extra — —x—x —x —x

$V_{GS} = V_{in} - V_{Th}$.

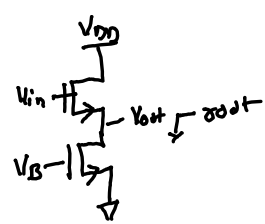
$\frac{\partial V_{GS}}{\partial V_{Th}} = -1. \quad \therefore \; g_m \times \eta = \frac{I_D}{V_{GS}} \times \frac{\partial V_{GS}}{\partial V_{Th}} \times \frac{\partial V_{Th}}{\partial V_{SB}} = -g_{mb}$

$\frac{\partial I_d}{\partial V_{SB}} = \frac{-\partial I_d}{\partial V_{BS}} = -1 \times -g_{mb} = g_{mb}$

⇒ even $R_S \Rightarrow \infty$ the gain of amplifier is always less than 1 ∴ i.e $\frac{g_m}{g_m + g_{mb}}$



⇒ if V_{GS} is increased by the factor $\sqrt{2}$ current in resistor increase by the factor of 2 this causes Non-linearity to resolve this the resistor is replaced by constant current source. which is in saturation.



$$r_{out} = \frac{1}{g_m + g_{mb}}$$

$$A_V = \frac{g_m}{g_m + g_{mb}}.$$