## MOSFET Characteristics

### MOSFET I/V Characteristics

- The I/V characteristic (current/voltage) of a MOSFET is described as the operation in the triode and saturation region. The derivation at the I/V characteristic is referred as the gradual channel approximation. Figure 1 describes the cross section of an n-channel MOSFET.

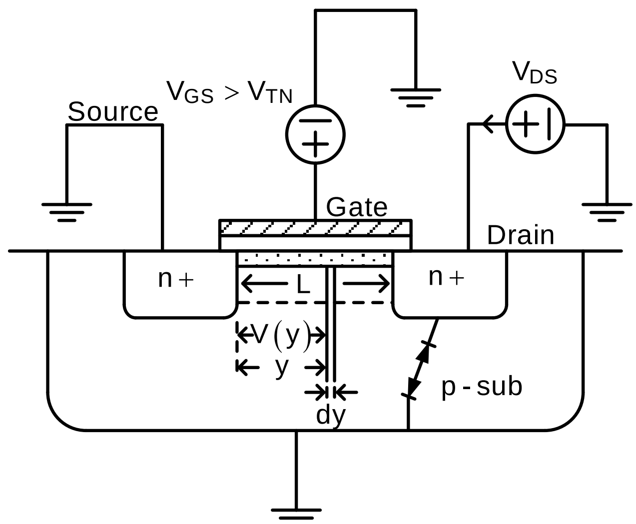


Figure 1 : Cross Section of n-channel MOSFET

- The value for $V_{GS}$ for the channel at charge corners is formed under the gate oxide between source and drain is referred as threshold voltage, $V_{TN}$.

- Being a four terminal device, with the drain and source interchangable the substrate is reversed biased in a single well process to alleviate the substrate current induction.

- With respect to the source of the transistor the voltage of the channel a distance y away from the source is labeled $V(y)$. The charge per unit area in the inversion layer is given by:

$$Q'_{ch} = C'_{ox}\left[V_{GS} - V(y)\right] \qquad (1\text{-}1)$$

- However a charge, $Q'_b$ is present in the inversion layer from the application of the threshold voltage, $V_{TN}$ between the drain and source and is given by:

$$Q'_1 = C'_{ox}V_{TN} \qquad (1\text{-}2)$$

- The total charge available in the channel, for conduction of a current between the drain and source is given by:

$$Q_1'(y) = C_{ox}'\left(V_{GS} - V(y) - V_{TN}\right) \quad (1\text{-}3)$$

where $Q_1'(y) =$ change in the inverted channel

- The differential resistance at the channel region with a length dy and a width W is given by:

$$dR = \frac{1}{\mu_n Q_1'(y)}\left(\frac{dy}{W}\right) \quad (1\text{-}4)$$

Where $\mu_n$ is the average electron mobility through the channel with units of $cm^2$/V.sec. The mobility is simply a ratio of the electron velocity cm/sec to the electric field V/cm.

- The differential voltage drop across the differential resistance is given by

$$dV(y) = I_D dR = \frac{I_D}{W\mu_n Q_1'(y)} dy \quad (1\text{-}5)$$

$$\Rightarrow I_{DS}(dy) = W\mu_n C_{ox}'\left(V_{GS} - V(y) - V_{TN}\right) dV(y) \quad (1\text{-}6)$$

- The transconductance parameter for a MOSFET is defined as

$$K_n = \mu_n\left(C_{ox}'\right) \quad (1\text{-}7)$$

- The current can be obtained by integrating the left side of equation (1) from source to drain, that is form 0 to L and the right side from 0 to $V_{DS}$.

$$I_{DS}\int_0^L dy = W(K_n)\int_0^{V_{DS}}\left(V_{GS} - V(y) - V_{TN}\right) dV(y) \quad (1\text{-}8)$$

$$\Rightarrow I_{DS} = K_n\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_{TN}\right)V_{DS} - \frac{V_{DS}^2}{2}\right] \text{for } V_{GS} \geq V_{TN} \text{ and } V_{DS} \leq V_{GS} - V_{TN} \quad (1\text{-}9)$$

- This equation is valid when the MOSFET is operating in the triode region. This is the case when the induced channel extends from the source to the drain.

- The parabolic plots of equation (9) for different values of $V_{GS}$, indicating the current capability at the device increase with $V_{GS}$ is illustrated as:

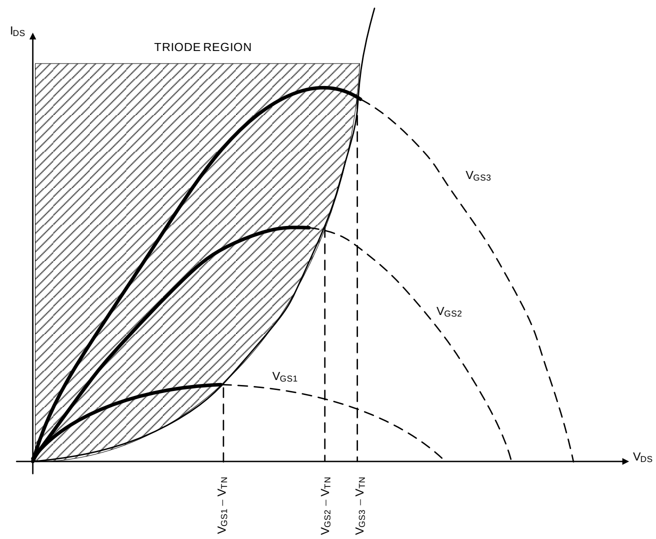


Figure 2 : $I_{DS}$ vs $V_{DS}$ in triode region

- The drain source voltage is called $V_{DS,sat} = V_{GS} - V_{TN}$ when the channel becomes pinched off at the drain channel interface. Further increase in $V_{DS}$ do not cause an increase in the drain current.

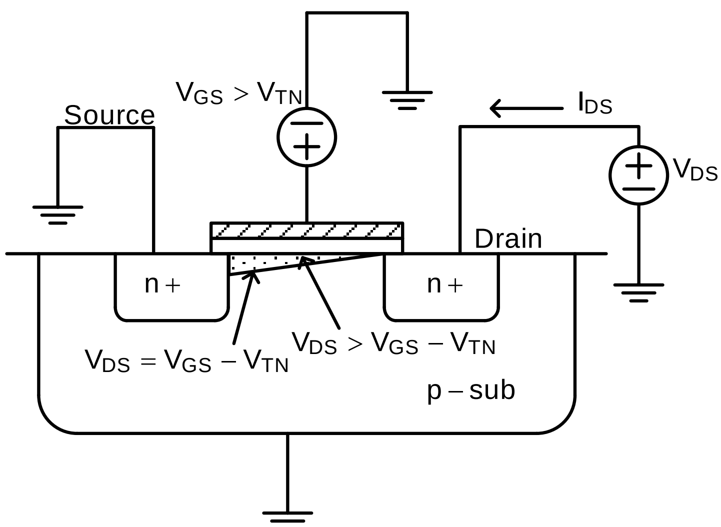


Figure 3 : The MOSFET in saturation (pinched off)

- When a MOSFET is operated with its channel pinched off, that is $V_{DS} \geq V_{GS} - V_{TN}$ and $V_{GS} \geq V_{TN}$. It is operating in the saturation region. Calculating $\partial I_{DS}/\partial V_{DS}$ from equation (9) and substituting $V_{DS,sat} = V_{GS} - V_{TN}$, to obtain a peak current at:

$$I_{DS} = \frac{1}{2}K_n' \frac{W}{L}\left(V_{GS} - V_{TN}\right)^2 \text{ for } V_{DS} - V_{TN} \text{ and } V_{GS} \geq V_{TN} \qquad (1\text{-}10)$$

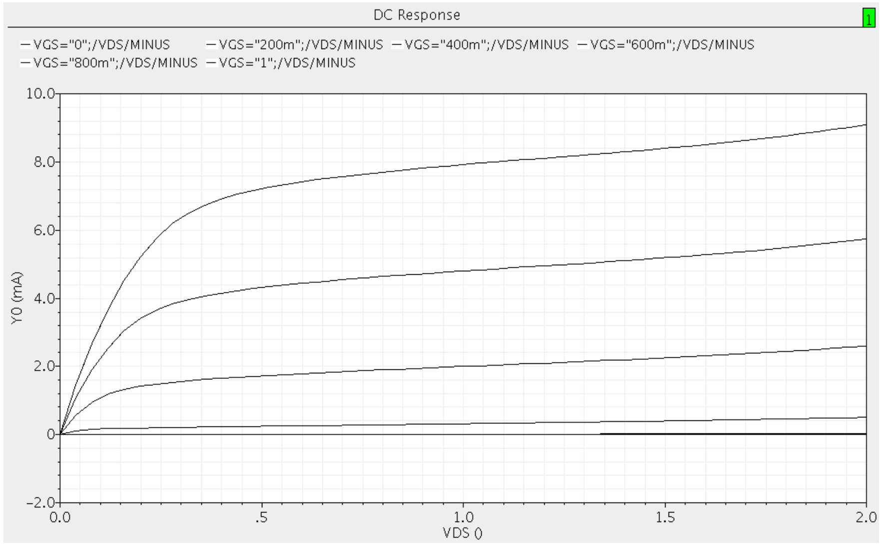


Figure 4 : I/V Characteristics of MOSFET

- Notice how the device appears to go into saturation earlier than predicted by $V_{DS} = V_{GS} - V_{TN}$. To understand this phenomenon, recall from $Q'(y)$. If $V(y)$ approaches $V_{GS} - V_{TN}$, then $Q'(y)$ drops to zero. In other words if $V_{DS}$ is greater than $V_{GS} - V_{TN}$, then the inversion layer stops at $y \le L$ and the channel is pinched off. As $V_{DS}$ increases further, the point at which $Q'(y)$ equals zero gradually moves towards the source.

- With the above explanation $Q'(y)$ is re-examined for a saturated device. Since $Q'(y)$ is the density at mobile charge, the integral of left side of equation (8) ,must be taken from $y = 0$ to $y = L'$, where $L'$ is the effective channel length, a point at which $Q_1$ drops to zero and the right side from $V(y) = 0$ to $V(y) = V_{GS} - V_{TN}$, resulting in

$$I_{DS} = \frac{1}{2} K_n' \frac{W}{L} (V_{GS} - V_{TN})^2 \text{ for } V_{DS} > V_{GS} - V_{TN} \text{ and } V_{GS} \ge V_{TN} \quad (1\text{-}11)$$

- In above analysis it is assumed that the bulk and the source at the transistor were tied to ground for a n-channel device. To understand the phenomenon at body effect, suppose for
$V_S = V_D = 0$ and $V_G$ is less than $V_{TN}$ so that a depletion region is formed.

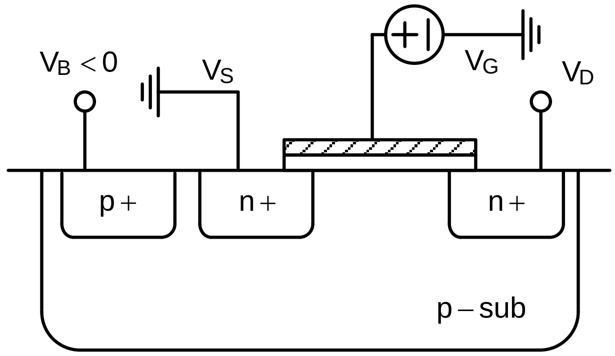


Figure 5 : MOSFET with bulk voltage.

- As $V_B$ becomes more negative more holes are attracted to the substrate connection, leaving a larger negative charge behind, the depletion region becomes wider.

- As the threshold voltage is a function at the total charge increases, $V_{TN}$ also increases. This is called the body effect or the back gate effect and is illustrated in Figure 6 below.

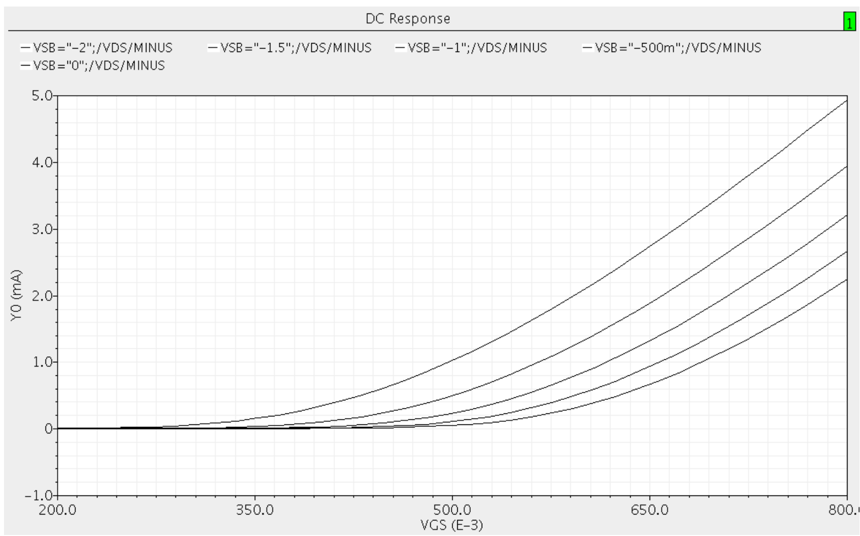


Figure 6 : $I_{DS}$ vs $V_{GS}$ for different $V_{SB}$

- The transconductance, $g_m$ of a MOSFET is defined as the sensitivity at the device, in which it indicates how well a device converts a voltage to curent.

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = K_n \left(\frac{W}{L}\right)(V_{GS} - V_{TN}) \tag{1-12}$$

$$g_m = \sqrt{2K_n \left(\frac{W}{L}\right) I_{DS}} \tag{1-13}$$

$$g_m = \frac{2I_{DS}}{V_{GS} - V_{TN}} \tag{1-14}$$

- From the expression of $g_m$ the behaviour is studied as a function of overdrive voltage, $V_{GS} - V_{TN}$ and drain current, $I_{DS}$

- From equation $(1\text{-}12)$ with $(W/L)$ constant, the transconductance is proportional to the overdrive voltage, where an increase of the overdrive voltage increases the sensitivity at the MOSFET as the inversion channel become wider as shown in Figure 7.

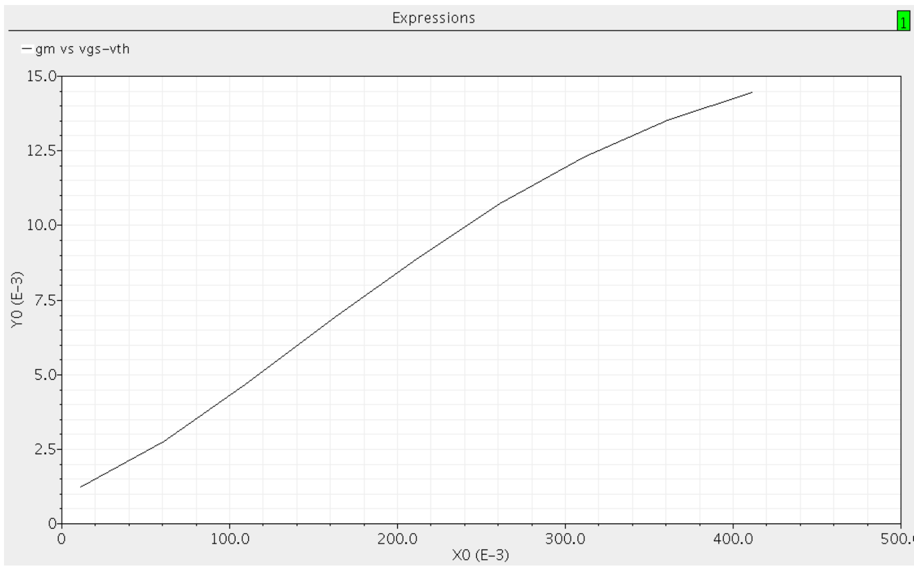


Figure 7 : $g_m$ vs $V_{GS} - V_{TN}$ when $W/L$ constant

- Given a constant $(W/L)$ and $V_G$ is slightly more than the threshold, $V_{TN}$, the sensitivity, $g_m$ increases with the channel induced current, eventually to be limited by the channel pinched off in saturation as shown in Figure 8.

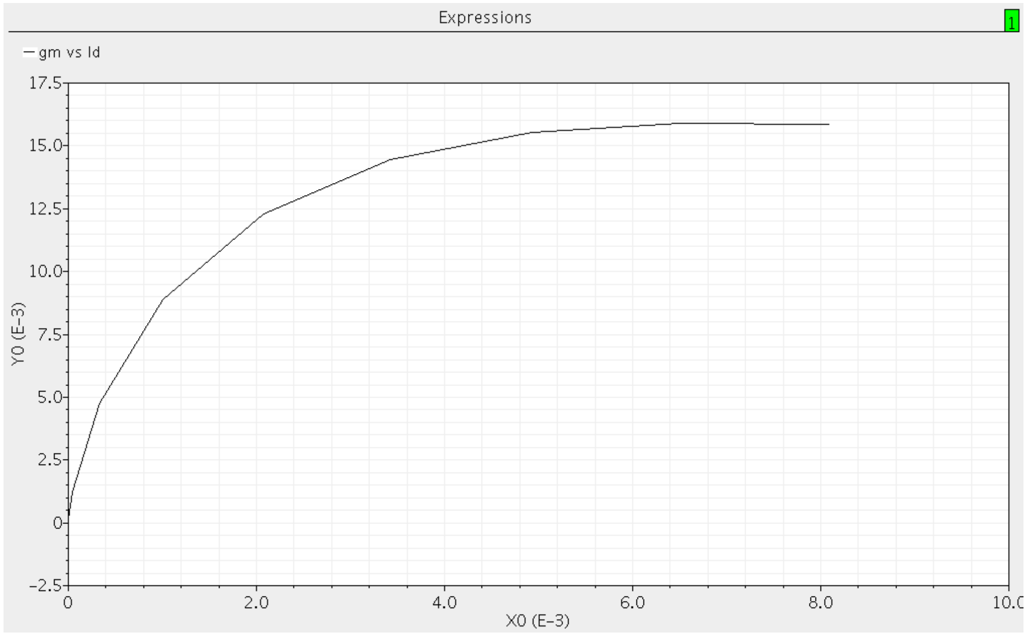


Figure 8 : $g_m$ vs $I_{DS}$ when $W/L$ constant

- Given a constant $I_{DS}$ , from equation (14), $g_m$ is inversely proportional to the overdrive voltage, as the voltage to current conversion is limited by the constant $I_{DS}$ and increasing $V_{GS}$ as shown in Figure 9.

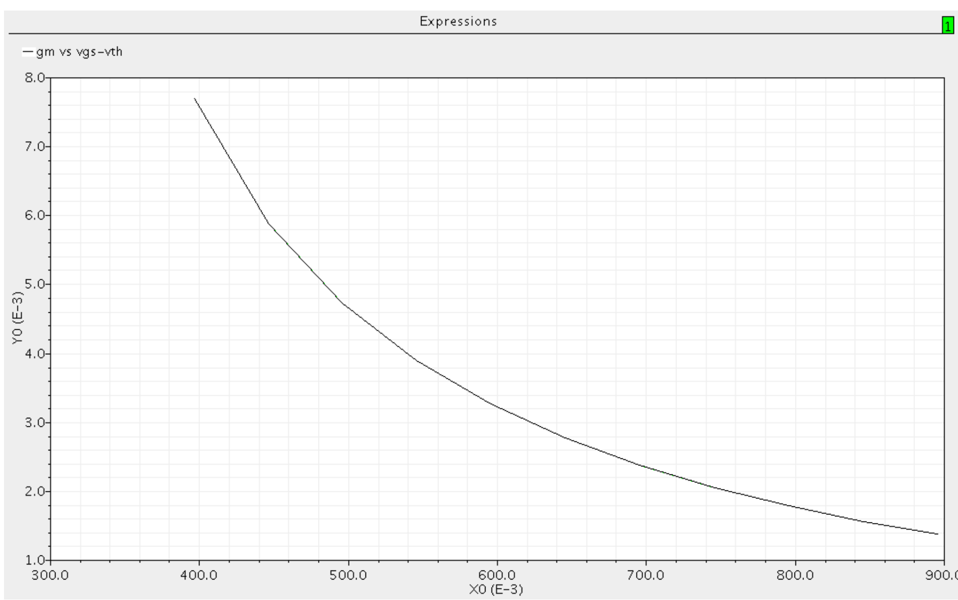


Figure 9 : $g_m$ vs $V_{GS} - V_{TN}$ when $I_{DS}$ constant