The Arrows in the symbols indicate the normal direction of current flow and it indicates the Source terminal.
Current-voltage characteristics: \( i_D - v_{DS} \)

\[ i_D = i_D(i_G, v_{DS}, v_{GS}) \]

Saturation Region

Triode Region

\( V_{DS} \leq V_{GS} - V_t \)

\( V_{DS} \geq V_{GS} - V_t \)

\( V_{GS} = V_t + 1 \)

\( V_{GS} = V_t + 2 \)

\( V_{GS} = V_t + 3 \)

\( V_{GS} = V_t + 4 \)

\( V_{GS} = V_t + 5 \)

\( V_{SD} \leq V_{GS} - V_t \)

\( V_{SD} \geq V_{GS} - V_t \)

\( V_{GS} = V_t - 1 \)

\( V_{GS} = V_t - 2 \)

\( V_{GS} = V_t - 3 \)

\( V_{GS} = V_t - 4 \)

\( V_{GS} = V_t - 5 \)
Three distinct regions of operation:

1. **Cut-off Region**
2. **Triode Region**
3. **Saturation Region**
   - Saturation region: used for amplifier applications
   - Cut-off & Triode Region: used for Switch applications

Relative terminal voltage of the enhancement type NMOS and PMOS for operation in the # regions
NMOS

I - $v_{GS} \leq V_t$  
No channel  **cut-off Region**

\[ i_D = 0 \]

II - $v_{GS} > V_t$  
Induced channel

1) $v_{DS} \leq v_{GS} - V_t; \ (v_{GD} \geq V_t)$  
   (continuous channel)  **Triode Region**

\[ i_D = k_n' \frac{W}{L} \left[ (v_{GS} - V_t) \cdot v_{DS} - \frac{1}{2} v_{DS}^2 \right] \]

$k_n' \equiv$ Process Transconductance Parameter

$\frac{W}{L} \equiv$ Aspect Ratio

For $v_{DS}$ very small, Linear relation $\Rightarrow$
Operation like resistor $r_{DS}$

2) $v_{DS} \geq v_{GS} - V_t; \ (v_{GD} \leq V_t)$  
   (pinched-off channel)  **Saturation Region**

\[ i_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2 \]

PMOS

I - $v_{GS} \geq V_t$  
No channel  **cut-off Region**

\[ i_D = 0 \]

II - $v_{GS} < V_t$  
Induced channel

1) $v_{DS} \geq v_{GS} - V_t; \ (v_{GD} \leq V_t)$  
   (continuous channel)  **Triode Region**

\[ i_D = k_p' \frac{W}{L} \left[ (v_{GS} - V_t) \cdot v_{DS} - \frac{1}{2} v_{DS}^2 \right] \]

$k_p' \equiv$ Process Transconductance Parameter

$\frac{W}{L} \equiv$ Aspect Ratio

For $|v_{DS}|$ very small, Linear relation $\Rightarrow$
Operation like resistor $r_{DS}$

2) $v_{DS} \leq v_{GS} - V_t; \ (v_{GD} \geq V_t)$  
   (pinched-off channel)  **Saturation Region**

\[ i_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2 \]
Role of the Substrate Body Effect

In many application Source and Body are connected $\Rightarrow$ Substrate does not have any role

All the above characterization is valid with no change

In Integrated Circuit (IC) the body is common to many MOS transistors:

- In NMOS the body is connected to the lowest voltage
- In PMOS the body is connected to the highest voltage

The resulting reverse bias between Source and Body $V_{SB}$ will have an effect on the operation:

This effect can be simply represented by a change in the threshold voltage:

$$V_t = V_{t0} + \gamma \left( \sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f} \right)$$

$V_{t0}$ $\equiv$ Threshold at $V_{SB} = 0$;

$\phi_f$ $\equiv$ Physical parameter; typically $(2\phi_f) \sim 0.6 \text{ V}$

$\gamma = \frac{\sqrt{2qN_A \epsilon_s}}{C_{ox}}$ $\equiv$ is a fabrication process parameter; typically $\gamma \sim 0.4 \text{ V}^{1/2}$