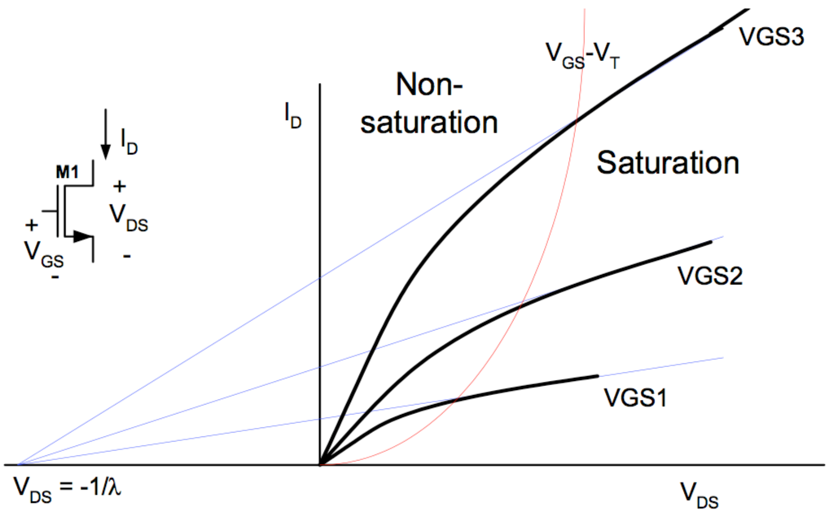
1. MOSFET Equations

a) N-channel MOSFET

Cut Off	$V_{GS} \le V_T$	$I_{DS} = 0$
Linear	$V_{GS} > V_T$, $V_{DS} \le V_{GS} - V_T$	$I_{DS} = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right](1 + \lambda V_{DS})$
Saturation	$V_{GS} > V_T$, $V_{DS} > V_{GS} - V_T$	$I_{DS} = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$

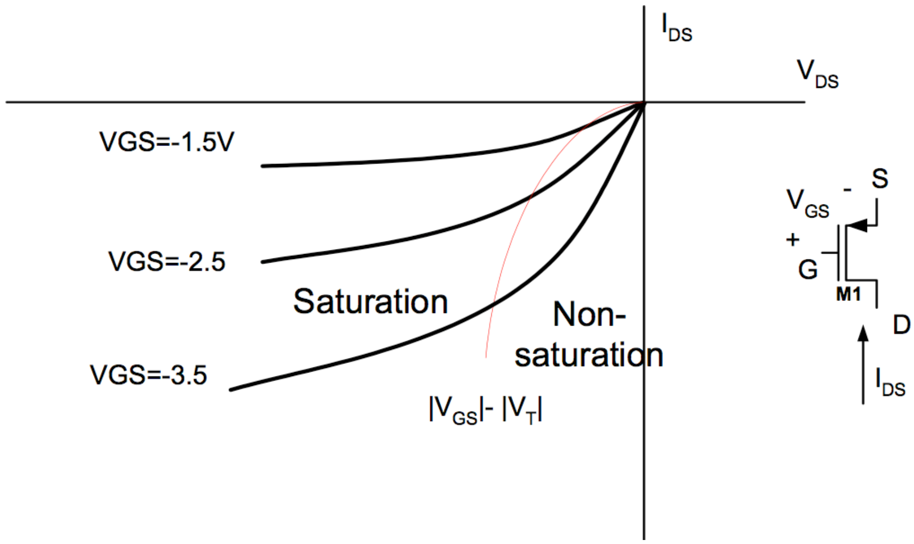


The simplest model in SPICE (Level 1 or default model) uses the above equations.

Parameter	SPICE Parameter	Units	Typical Values
$\mu_n C_{ox}$	KP	A/V^2	200μ
V_{T0}	VTO	V	0.5 – 1.0
λ	LAMBDA	V^{-1}	0.05 – 0.005

b) P-channel MOSFET

Cut Off	$V_{SG} \le \lvert V_T \rvert$	$I_{SD} = 0$
Linear	$V_{SG} > \lvert V_T \rvert$, $V_{SD} \le V_{SG} - \lvert V_T \rvert$	$I_{SD} = \mu_p C_{ox} \frac{W}{L}\left[(V_{SG} - \lvert V_T \rvert)V_{SD} - \frac{V_{SD}^2}{2}\right](1 + \lambda V_{SD})$
Saturation	$V_{SG} > \lvert V_T \rvert$, $V_{SD} > V_{SG} - \lvert V_T \rvert$	$I_{SD} = \frac{1}{2}\mu_p C_{ox} \frac{W}{L}(V_{SG} - \lvert V_T \rvert)^2(1 + \lambda V_{SD})$



Example)
$V_S = 4$ V, $V_G = 2$ V, $V_D = 1$ V
$V_T = -0.8$ V, $\lambda = 0$, Kp = 100 $\mu A/V^2$
W = 10 μm, L= 2 μm
Find MOSFET type, operation region, I_{DS}.

- Solution

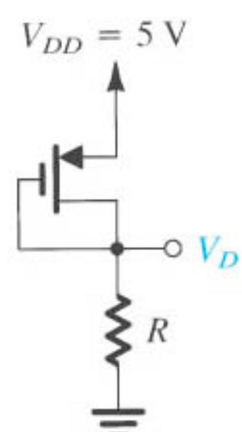
$$|V_{DS}| > |V_{GS}| - |V_T| \Rightarrow saturation$$

$$I_{SD} = \frac{100\mu}{2}\frac{10\mu}{2\mu}(2 - |-0.8|)^2(1+0) = 360\mu A$$

$$I_{DS} = -360\mu A$$

2. MOSFET Circuits

Example) The PMOS transistor has $V_T = -2$ V, Kp = 8 $\mu A/V^2$, L = 10 μm, $\lambda = 0$.
Find the values required for *W* and *R* in order to establish a drain current of 0.1 mA and a voltage V_D of 2 V.



- Solution

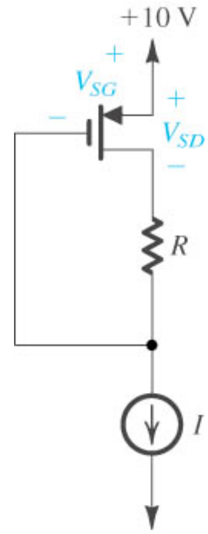
$$V_D = V_G \Rightarrow V_{SD} > V_{SG} - |V_T| \Rightarrow saturation$$

$$|I_{DS}| = \frac{1}{2}Kp\frac{W}{L}(V_{SG} - |V_T|)^2(1+\lambda V_{SD}) = \frac{8\mu}{2}\frac{W}{10\mu}(3-2)^2(1+0) = 0.1mA$$

$$I_R = \frac{V_D}{R} = \frac{2}{R} = 0.1mA$$

$$W = 250\mu m, \qquad R = 20k\Omega$$

Example) The PMOS transistor has V_T = -1 V, Kp = 8 μA/V^2,
W/L = 25, λ = 0.
For I = 100 μA, find the V_{SD} and V_{SG} for R = 0, 10k, 30k, 100k.



- Solution
λ = 0 (no channel length modulation)

1) $R = 0$

$$V_D = V_G \Rightarrow V_{SD} > V_{SG} - |V_T| \Rightarrow saturation$$

$$I_{SD} = \frac{1}{2} Kp \frac{W}{L} (V_{SG} - |V_T|)^2 = \frac{8\mu}{2} \cdot 25 \cdot (V_{SG} - 1)^2 = 100\mu$$

$$V_{SG} = 2V \quad V_{SD} = 2V$$

2) $R = 10k$

$$V_D - V_G = IR = 100\mu \cdot 10k = 1 \Rightarrow V_{SD} = V_{SG} - |V_T| \Rightarrow saturation \quad or \quad linear$$

$$I_{SD} = \frac{1}{2} Kp \frac{W}{L} (V_{SG} - |V_T|)^2 = \frac{8\mu}{2} \cdot 25 \cdot (V_{SG} - 1)^2 = 100\mu$$

$$V_{SG} = 2V \quad V_{SD} = 1V$$

3) $R = 30k$

$$V_D - V_G = IR = 100\mu \cdot 30k = 3 \Rightarrow V_{SD} < V_{SG} - |V_T| \Rightarrow linear$$

$$I_{SD} = Kp \frac{W}{L} ((V_{SG} - |V_T|)V_{SD} - \frac{V_{SD}^2}{2}) = 8\mu \cdot 25 \cdot ((V_{SD} + 3 - 1)V_{SD} - \frac{V_{SD}^2}{2}) = 100\mu$$

$$V_{SD} \approx 0.24V \quad V_{SG} = 3.24V$$

4) $R = 100k$

$$V_D - V_G = IR = 100\mu \cdot 100k = 10 \Rightarrow V_{SD} < V_{SG} - |V_T| \Rightarrow linear$$

$$I_{SD} = Kp \frac{W}{L} ((V_{SG} - |V_T|)V_{SD} - \frac{V_{SD}^2}{2}) = 8\mu \cdot 25 \cdot ((V_{SD} + 10 - 1)V_{SD} - \frac{V_{SD}^2}{2}) = 100\mu$$

$$V_{SD} \approx 0.06V \quad V_{SG} = 10.06V$$