MOSFET Device

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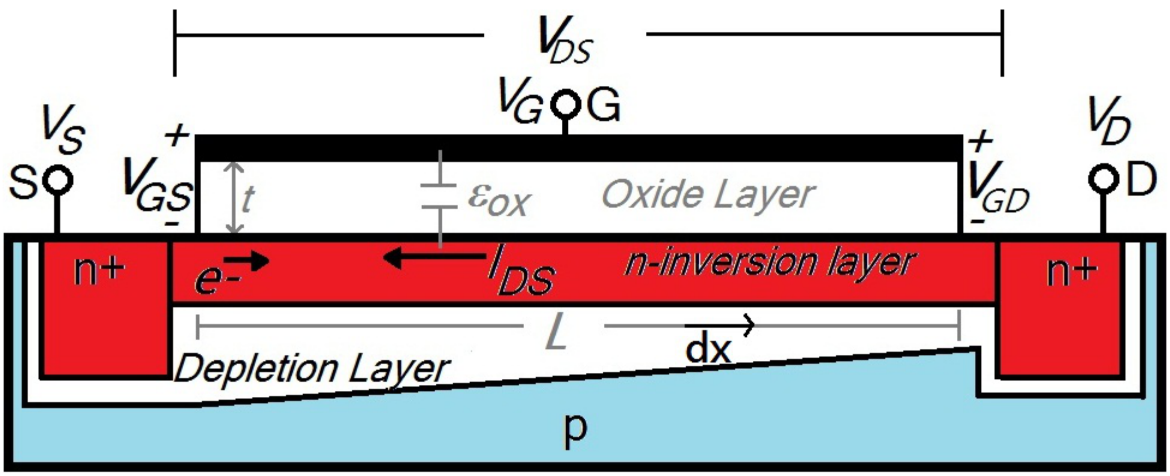
Reference : Sedra, Smith *Microelectronics Circuits*

1 Structure and Operation Mode



When $V_{GS} \sim 0$ **,** $V_{GS} \ll V_{TN}$

- **Cut-off mode**
- There is depletion region, but no n-channel
- $i_{DS} = 0$, as no channel for e^- to move

When $V_{GS} \gg V_{TN}$ **,** $V_{DS} < V_{GS} - V_{TN}$

- **Triode Mode**
- Channel established , there is a n-inversion layer
- i_{DS} exist, e^-flow from S to D , so conventional current I_{DS} flow from D to S

When $V_{DS} = V_{GS} - V_{TN}$ **(** $V_{GS} > V_{TN}$ **)**

- **Saturation mode**
- V_{DS} can not affect I_{DS} anymore

About I_{GS}

- The oxide layer is an insulator that block the current flow from the metal of G to semiconductor
- So $I_{GS} = 0$ (always)

2 Device Model

2.1 Capacitance of MOSFET

The Metal-Oxide-Semiconductor layer acts like a parallel plate capacitor, with capacitance

$$C_{ox} = \frac{\epsilon_{ox} WL}{T_{ox}}$$

- ϵ_{ox} : permitivity of oxide layer
- WL : area of the plate , $L = \max x$ is channel length , W is width of the device
- T_{ox} : Thickness of the insulating oxide layer

Therefore the capacitance per area is $c_{ox} = \frac{\epsilon_{ox}}{T_{ox}}$ Capacitance of a small strip dx

$$C_{ox} = c_{ox} W dx$$

2.2 Channel Voltage and E-field, Drift Velocity

$$V_{ch} = V_{GS} - V_{TN} - V(x)$$

$$E(x) = -\frac{dV(x)}{dx}$$

The charge carrier inside N-MOSFET is e-, with drift velocity as

$$\frac{dx}{dt} = v_d = -\mu_n E(x) = (-\mu_n)\left(-\frac{dV(x)}{dx}\right) = \mu_n \frac{dV(x)}{dx}$$

2.3 Charge Carrier in the channel strip, and the Channel Current

$$dq = (dC_{ox})V_{ch} = c_{ox} W \left(V_{GS} - V_{TN} - V(x)\right) dx$$

Thus, the drift current, which is the Drain-Source current is

$$I_{DS} = \frac{dq}{dt} = \frac{c_{ox} W \left(V_{GS} - V_{TN} - V(x)\right) dx}{dt} = c_{ox} W \left(V_{GS} - V_{TN} - V(x)\right) v_d$$

$$\iff \quad I_{DS} = c_{ox} W \left(V_{GS} - V_{TN} - V(x)\right) \mu_n \frac{dV(x)}{dx}$$

$$\iff \quad I_{DS} dx = c_{ox} \mu_n W \left(V_{GS} - V_{TN} - V(x)\right) dV(x)$$

Boundary condition : $x \in [0, L]$, $V \in [0, V_{DS}]$

$$\iff \int_{x=0}^{x=L} I_{DS} dx = \int_{V=0}^{V=V_{DS}} c_{ox}\mu_n W \left(V_{GS} - V_{TN} - V(x)\right) dV(x)$$

$$\iff I_{DS} L = c_{ox}\mu_n W \left(\left(V_{GS} - V_{TN}\right) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

$$\iff I_{DS} = \frac{c_{ox}\mu_n W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$$

Conisder $c_{ox}\mu_n$ is constant (although actually not), denoted as k_n'

$$I_{DS} = k_n' \left(\frac{W}{L}\right) \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$$

If $\frac{W}{L}$ is also plugged into k_n' ,

$$I_{DS} = K_n \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$$

In triode region

$$I_{DS}(Triode) = K_n \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$$

In saturation region, $V_{DS} = V_{GS} - V_{TN}$

$$I_{DS}(Saturation) = \frac{K_n}{2} \left(V_{GS} - V_{TN}\right)^2$$

3 Summary

Mode	V_{GS}	V_{DS}	CompleteI_D
Cutoff	$V_{GS} < V_{TN}$	/	0
Triode	$V_{GS} \geq V_{TN}$	$V_{DS} < V_{DS,Saturation}$	$I_D = k_n \left(\frac{W}{L}\right) \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$
Saturation	$V_{GS} \geq V_{TN}$	$V_{DS} > V_{DS,Saturation} = V_{GS} - V_{TN}$	$I_D = \frac{k_n}{2} \left(\frac{W}{L}\right) \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$

$k_n = c_{ox}\mu_{ox}$

$-END-$