First-pass MOSFET Model

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“First-pass” MOSFET Model

Source: B. Murmann (Textbook p.19)
nMOST with $V_{GS}=0$ and $V_{GS} > V_{Tn}$

Source: B. Murmann (Textbook p.20)
First-pass Model Assumptions

1. The current primarily depend on the number of mobile electrons in the channel times their velocity

2. The number of mobile electrons in the channel is set by the vertical electric field from gate to the conductive channel (gradual channel approximation)

3. The threshold voltage is constant along the channel: this assumption neglects the so called body effect (more on body effect later …)

4. The velocity of the electrons traveling from source to drain is proportional to the later electric filed in the channel
Model Assumptions

\[ Q_N(y) = C_{OX} \cdot (V_{GC}(y) - V_{Tn}) \]
\[ V_{GC}(y) = V_G - V(y) \]

Source: B. Razavi
nMOST in cut-off

- $V_{GS} < V_{Tn}$
- $Q_N = \text{inversion charge} = 0$

$\boldsymbol{I_D = 0}$
Channel profile for varying $V_{DS}$ (and $V_{GS} > V_{Tn}$)

Source: B. Murmann (Textbook p.21)

(a) $V_{DS} = 0$

(b) $0 < V_{DS} < V_{GS} - V_{Tn}$

(c) $V_{DS} = V_{GS} - V_{Tn}$

(d) $V_{DS} > V_{GS} - V_{Tn}$

Source: B. Murmann (Textbook p.21)
nMOST in triode (a.k.a. linear)

\[ I_D = \mu_n C_{OX} \frac{W}{L} (V_{GS} - V_{Tn} - V_{DS} / 2) V_{DS} \]

\[ C_{OX} \triangleq \frac{\varepsilon_{OX}}{t_{OX}}; \quad KP_n \triangleq \mu_n C_{OX}; \quad \beta \triangleq \mu_n C_{OX} \frac{W}{L} \]
nMOST in Saturation (1)

\[ I_D = \frac{\mu_n C_{OX} W}{2 L} (V_{GS} - V_{Tn})^2 \]
nMOST in saturation (2)

- Increase in lateral field $E(y)$ (that is $V_{DS}$) is compensated by decrease in $Q_N(y)$
- When $Q_N=0$ at the drain then $I_D$ saturates

After channel charge goes to 0, there is a high lateral field that ‘sweeps’ the carriers to the drain*, and drops the extra voltage (this is a depletion region of the drain junction)

* It is important to remember what a reverse biased PN junction does to minority carriers. Electrons (in the p-type material) get swept back into the n-region
I-V Characteristics (1)

(a)\[ I_D = V_{DS}/R_{on} \]

I_D [mA] \[ \begin{align*} &0.5 &1 &2 &3 &4 \\ \end{align*} \]

V_{DS} [V] \[ \begin{align*} &V_{DSsat} \\ \end{align*} \]

(b)\[ V_{GS3} - V_{Th} = 3V \]
\[ V_{GS2} - V_{Th} = 2V \]
\[ V_{GS1} - V_{Th} = 1V \]

I_D [mA] \[ \begin{align*} &0.5 &1 &2 &3 &4 \\ \end{align*} \]

V_{DS} [V] \[ \begin{align*} &V_{DSsat1} &V_{DSsat2} &V_{DSsat3} \\ \end{align*} \]

Source: B. Murmann (Textbook p.22)
I-V Characteristics (2)

Source: B. Murmann (Textbook p.23)
pMOST

Source: B. Murmann (Textbook p.24)
nMOST vs. pMOST

source: N. Weste and D. Harris
Channel Length Modulation (saturation) (1)

\[ I_D = \frac{\mu n C_{OX}}{2} \frac{W}{L - \Delta L} \left( V_{GS} - V_{Tn} \right)^2 \]

Source: B. Murmann (Textbook p.41)
Channel Length Modulation (2)

\[ I_D = \frac{\mu_n C_{OX}}{2} \frac{W}{L - \Delta L} (V_{GS} - V_{Tn})^2 \]

\[ \frac{1}{L - \Delta L} \approx \frac{1}{L} \left( 1 + \frac{\Delta L}{L} \right) \]

\[ \Delta L = f(V_{DS}) \]

\[ \frac{\Delta L}{L} \approx \lambda_n V_{DS} \]

- The channel length modulation parameter \( \lambda \) is a “crude” fudge factor.
- It is commonly acceptable to neglect \( \lambda V_{DS} \) in bias point calculations.

\[ I_D \approx \frac{\mu_n C_{OX}}{2} \frac{W}{L} (V_{GS} - V_{Tn})^2 (1 + \lambda_n V_{DS}) \]
MOS Transistor in the subthreshold region

- Around $V_{GS} = V_t$ the device physics become very complex and our simple derivations loses accuracy
  - Rule of thumb for long channel MOSTs: use $V_{GS} > V_t + 150$ mV (see plot on next page)

- For $V_{GS} \leq V_t$ the $I_D$ is exponentially related to $V_{GS}$ (subthreshold region of operation)
  - There is a growing number of applications that make use of the subthreshold operation

* NOTE: $150$ mV $\approx 6 \times V_{THERMAL} = 6 \times KT/q$
Model valid for $V_{OV} \geq 150$ mV

$g_{mD}$ [S/A] vs $V_{OV}$ [V]

- Dotted line: square-law equation
- Solid line: Actual MOSFET