Lecture11: MOSFET IV

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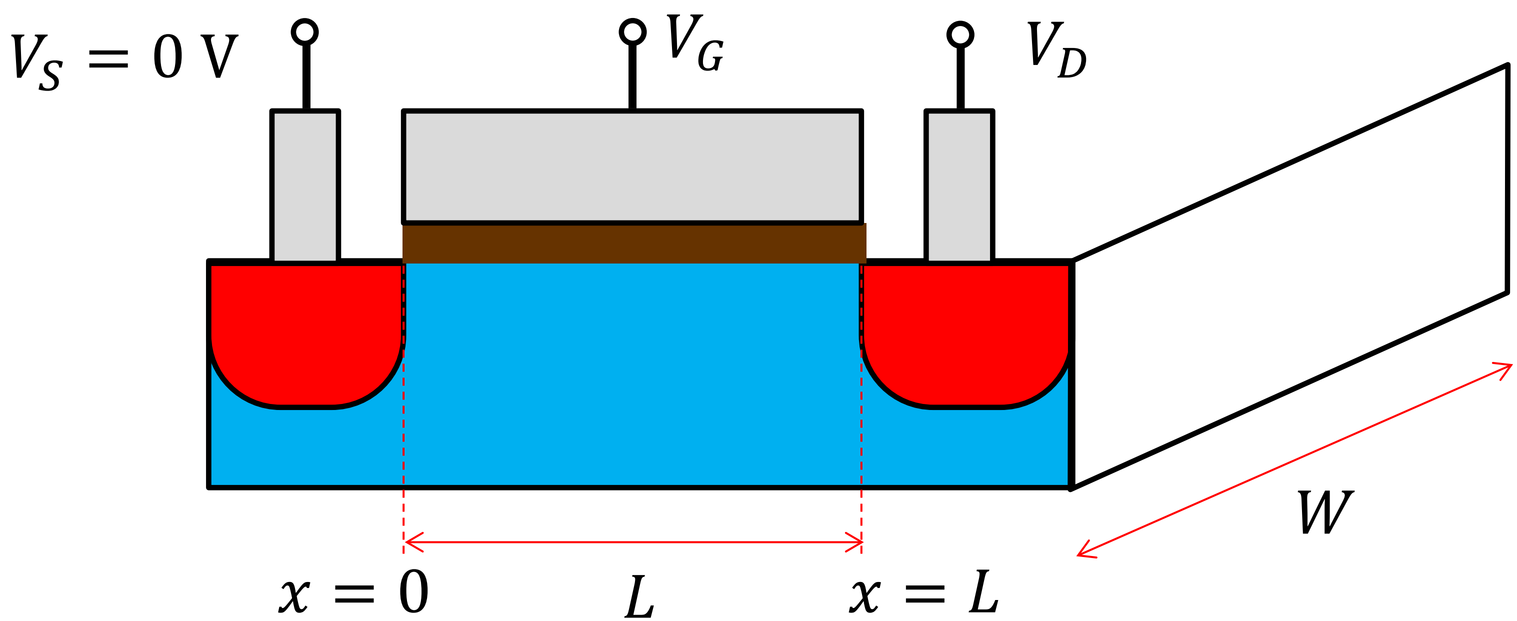
Device structure

- Two-dimensional cross-section
  - "Potential" can be dependent on the position, $V(x)$.



Derivation of IV (1)

- Drain current
  - Q_{elec} is the electron charge density *per unit length*.
  - It follows

$$Q_{elec} = WC_{ox}[V_G - V(x) - V_{TH}] \qquad \text{(Razavi 6.3)}$$

  - At a certain position of x, the current is given by

$$I(x) = Q_{elec}(x)\, v(x) \qquad \text{(Razavi 6.4)}$$

  - Also v is the electron velocity.

$$v = -\mu_n E = +\mu_n \frac{dV}{dx} \qquad \text{(Razavi 6.5 and 6.6)}$$

Derivation of IV (2)

- Drain current (Continued)
  - It is easy to understand that $I_D = I(x)$. The drain current is

$$I_D = WC_{ox}[V_G - V(x) - V_{TH}]\mu_n \frac{dV}{dx} \qquad \text{(Razavi 6.7)}$$

  - Simply re-arranging,

$$I_D dx = \mu_n C_{ox} W[V_G - V(x) - V_{TH}]dV$$

  - When integrated,

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_G - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

Triode mode

- Equation
  - A differential equation for $V(x)$

$$I_D = W C_{ox}[V_G - V(x) - V_{TH}]\mu_n \frac{dV}{dx}$$

  - Its solution

$$V(x) = V_G - V_{TH} - \sqrt{(V_G - V_{TH})^2 - \frac{2I_D}{\mu_n C_{ox} W} x}$$

  - Drain current

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_G - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

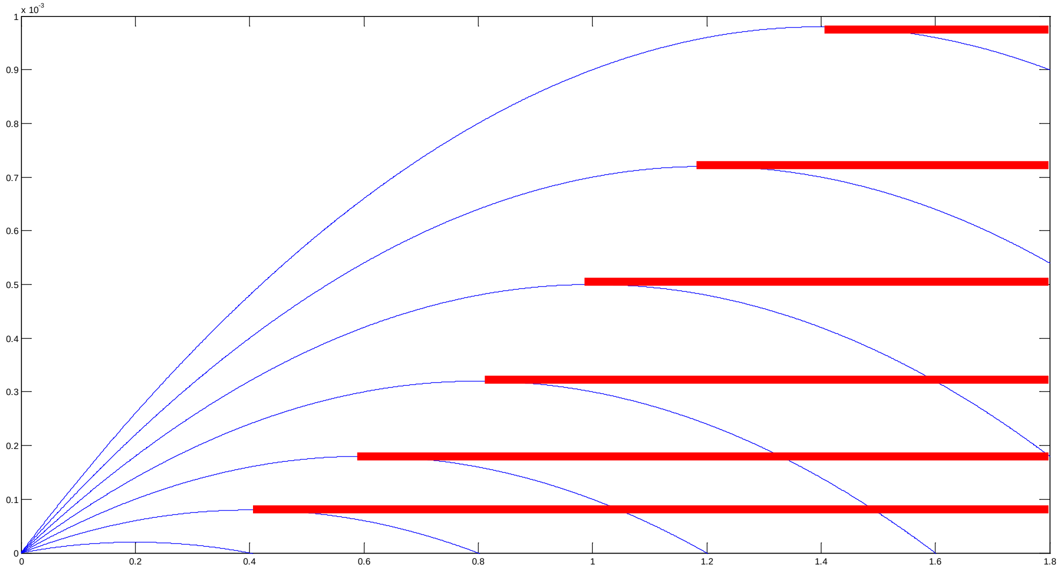
Saturation mode

- Current usually increases as the voltage increases…

$$|Q_{elec}| = WC_{ox}[V_G - V(x) - V_{TH}]$$ (Razavi 6.3)

  – What happens when $V(x) = V_G - V_{TH}$?

Current

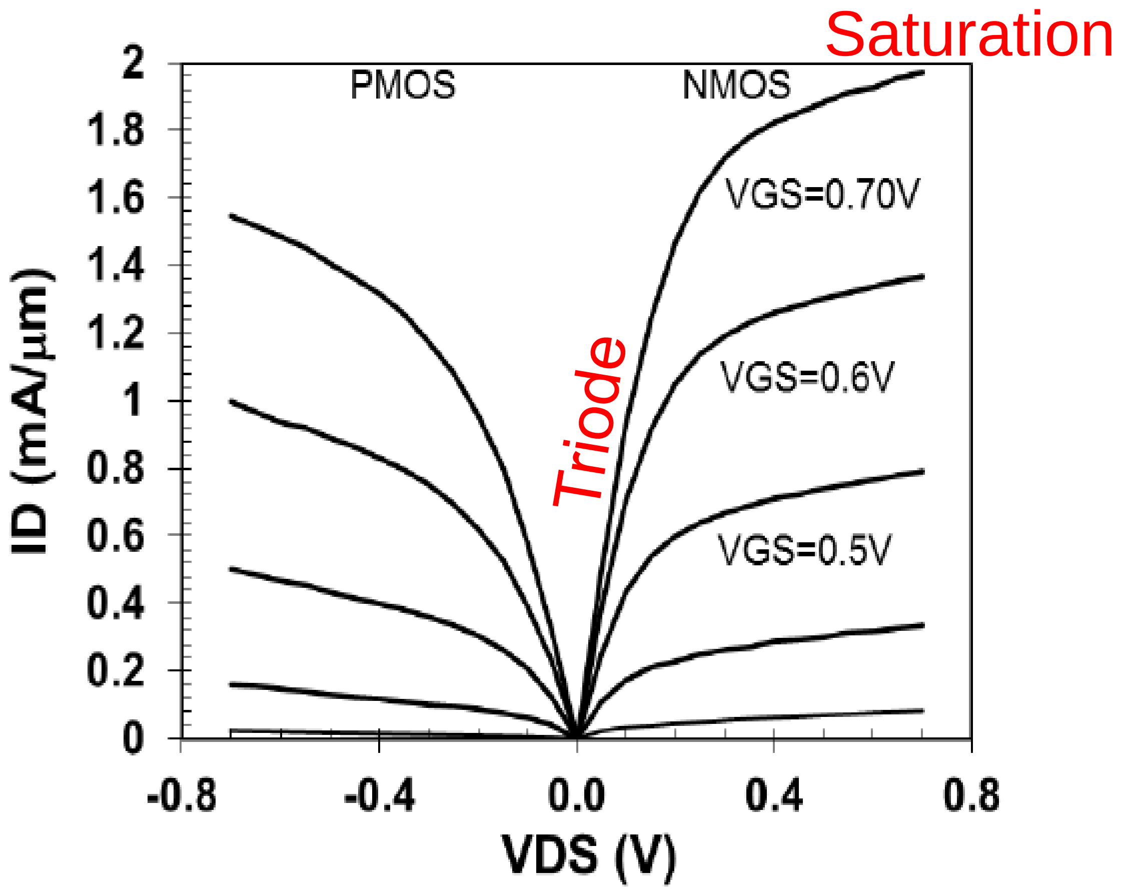


Voltage

🡐 Instead, the current is saturated. (Red lines)

State-of-the-art MOSFET

- C. Auth et al. (Intel, IEDM 2017)
  - Slight increase of I_D in the satruation region



Review on MOSFET IV

- When $V_G < V_{TH}$,
  - No drain current!

$$I_D = 0$$

- When $V_G > V_{TH}$,
  - Triode mode ($V_{DS} < V_G - V_{TH}$)

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_G - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

  - Saturation mode ($V_{DS} > V_G - V_{TH}$)

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_G - V_{TH})^2$$

  - For a short channel device, I_D increases slightly as V_{DS} increases.

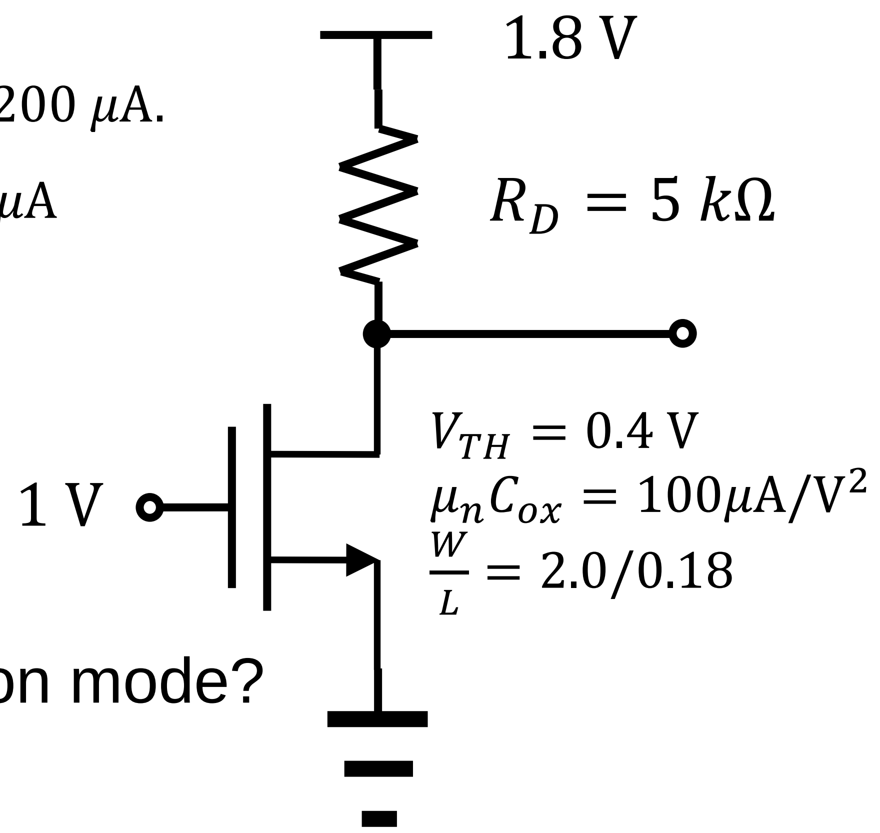
Example 6.6 (Razavi)

- Assume the saturation region.
  - The saturation current becomes $200\ \mu\text{A}$.

$$I_D = \frac{1}{2}\,100\mu\,\frac{2.0}{0.18}\,(1-0.4)^2 = 200\ \mu\text{A}$$

  - Then, the drain voltage is

$$V_D = 1.8 - 200\mu \times 5k = 0.8\ \text{V}$$



- Is the MOSFET in the saturation mode?

V_{out} versus V_{in}

- A table

V_{in} (V)	V_{out} (V)
0.0	1.8
<0.4	1.8
0.7	1.55
1.0	0.8
X	$X - 0.4$
1.8	Y

  – What are the values of X and Y?