Lecture11: MOSFET IV

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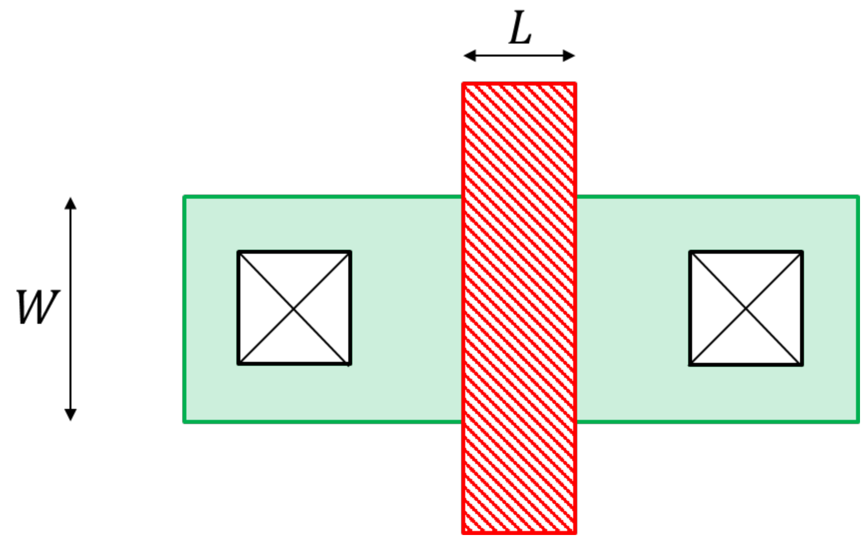
Q&A

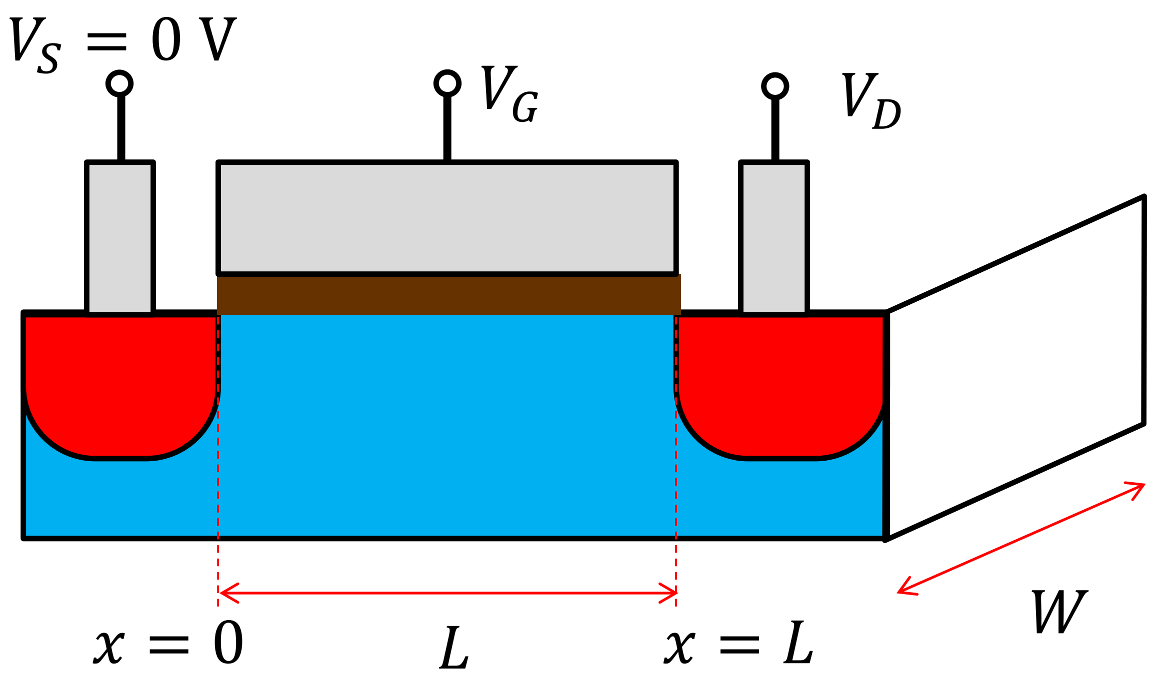
- Various definition of V_{TH}?
  - Which is the exact one?

- Linear $Q_{elec} - V_G$ relation. Why?
  - Surface potential pinning

Device structure

- 2D cross-section
  - "Potential" can be dependent on the position, $V(x)$.





Our goal: IV relation

- Current densities
  - In the 1D structure (along the x direction),

$$J_{n,x}^{diff} = qD_n \frac{dn}{dx}$$
$$J_{n,x}^{drift} = q\mu_n n\, E_x$$

  - We assume that the drift current is dominant.
- Terminal current
  - A correct sign!
  - In the 1D structure, the drain current would be

$$I_D = -Area \times \left(J_{n,x}^{diff} + J_{n,x}^{drift} \right)$$

  - Electron is not uniformly distributed along the vertical direction.

Derivation of IV (1)

- Drain current
  - Q_{elec} is the electron charge density *per unit length*.
  - It follows (with a correct sign)

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

  - 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,

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

Differential equation

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

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

  - Let's solve it together!

Its solution

- Equation
  - Its solution

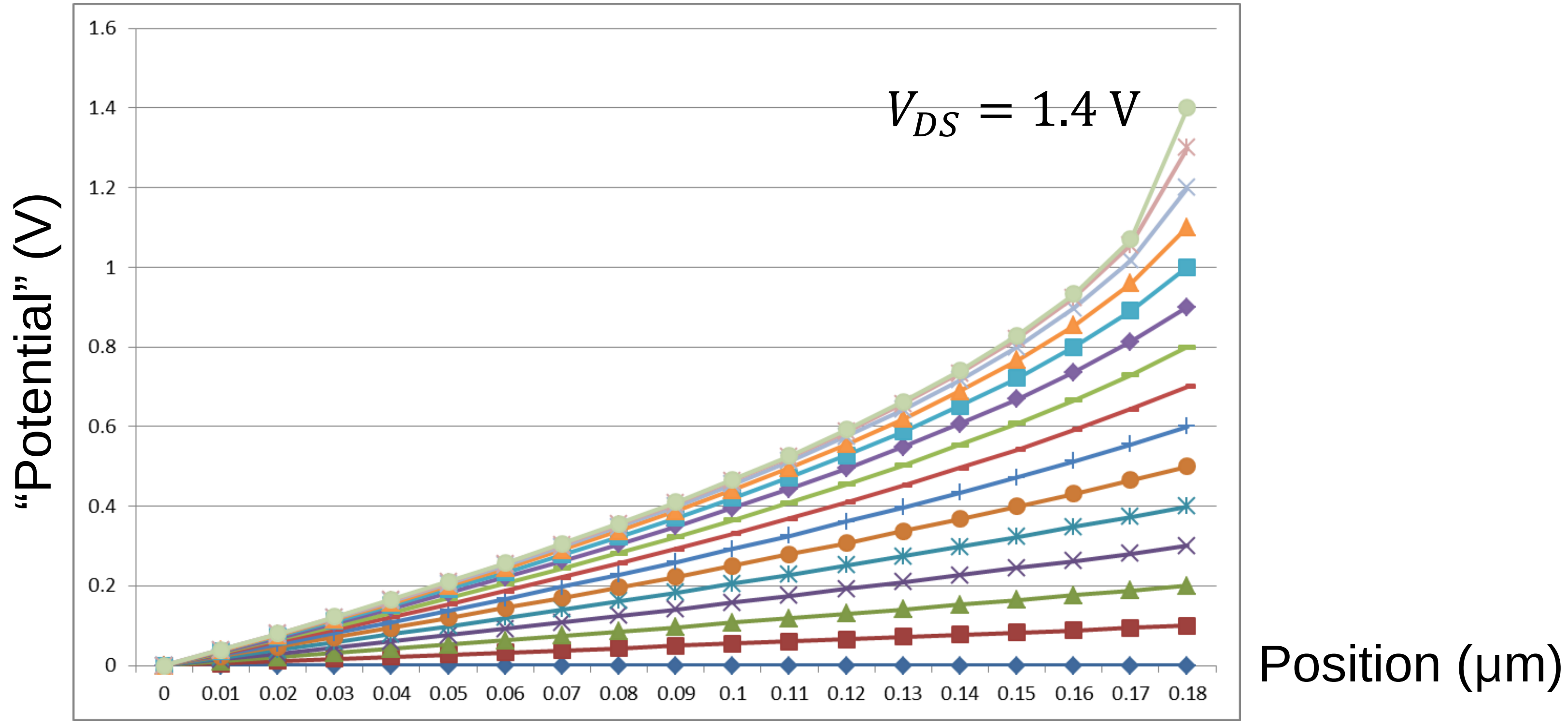
$$V(x) = V_G - V_{TH} - \sqrt{(V_G - V_{TH})^2 - \frac{2I_D}{\mu_n C_{ox} W} x}$$

  - Apply boundary conditions: $V(0) = V_S$ and $V(L) = V_D$
  - Drain current

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

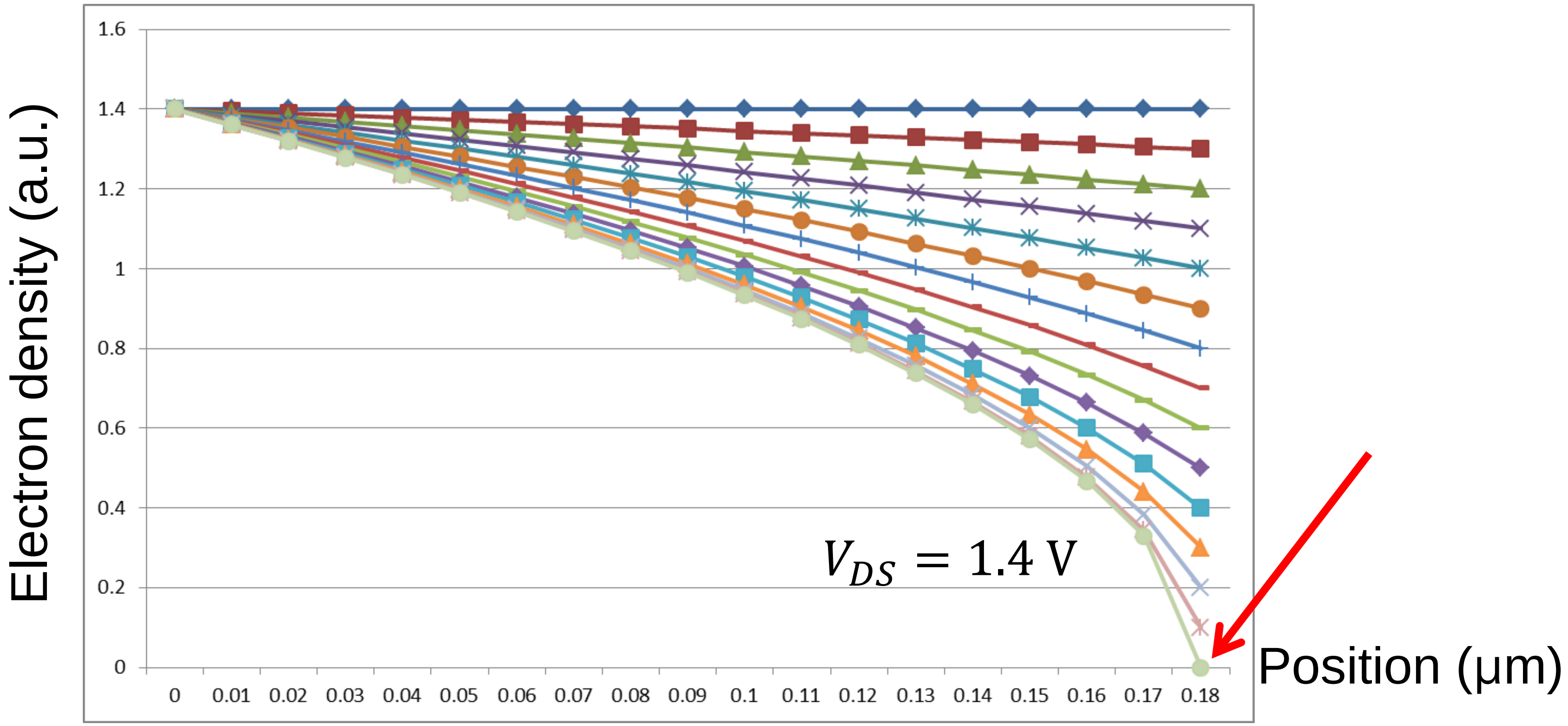
Solution, “potential”

- $V_{GS} = V_{DD}$=1.8 V. V_{DS} from 0 V to $V_{DD} - V_{TH}$=1.4 V



Solution, electron density

- $V_{GS} = V_{DD}$=1.8 V. V_{DS} from 0 V to $V_{DD} - V_{TH}$=1.4 V

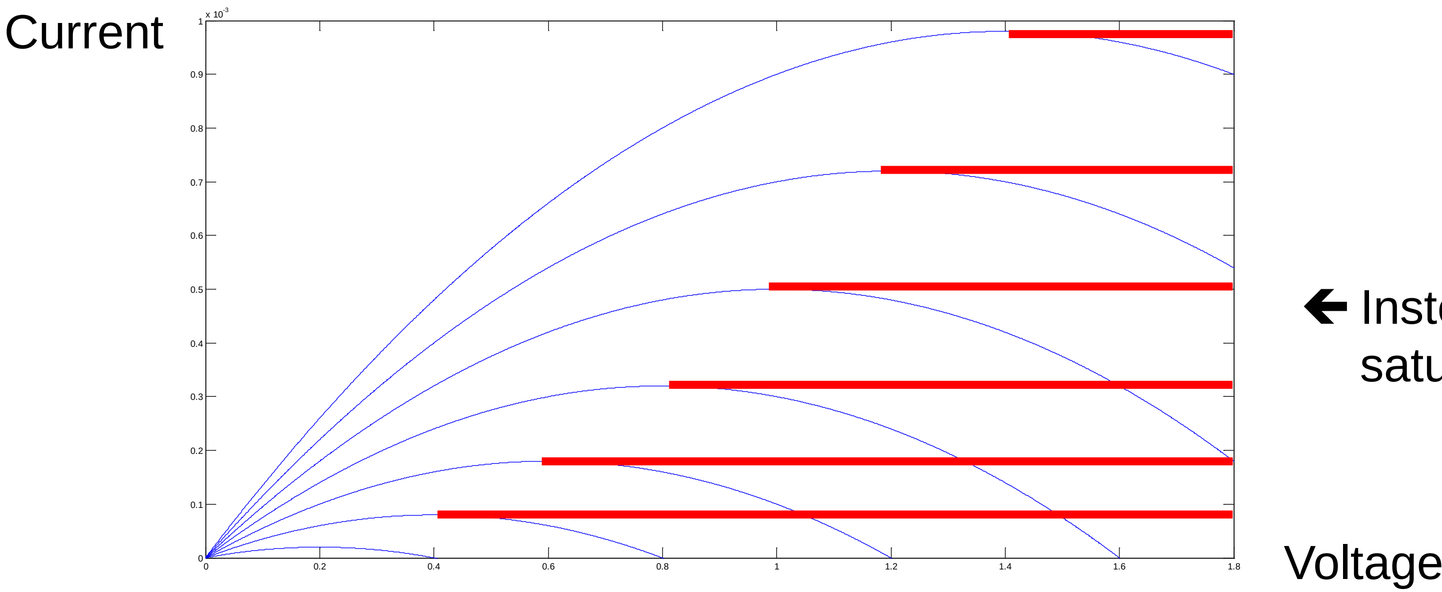


Saturation mode

- Current usually increases as the voltage increases…

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

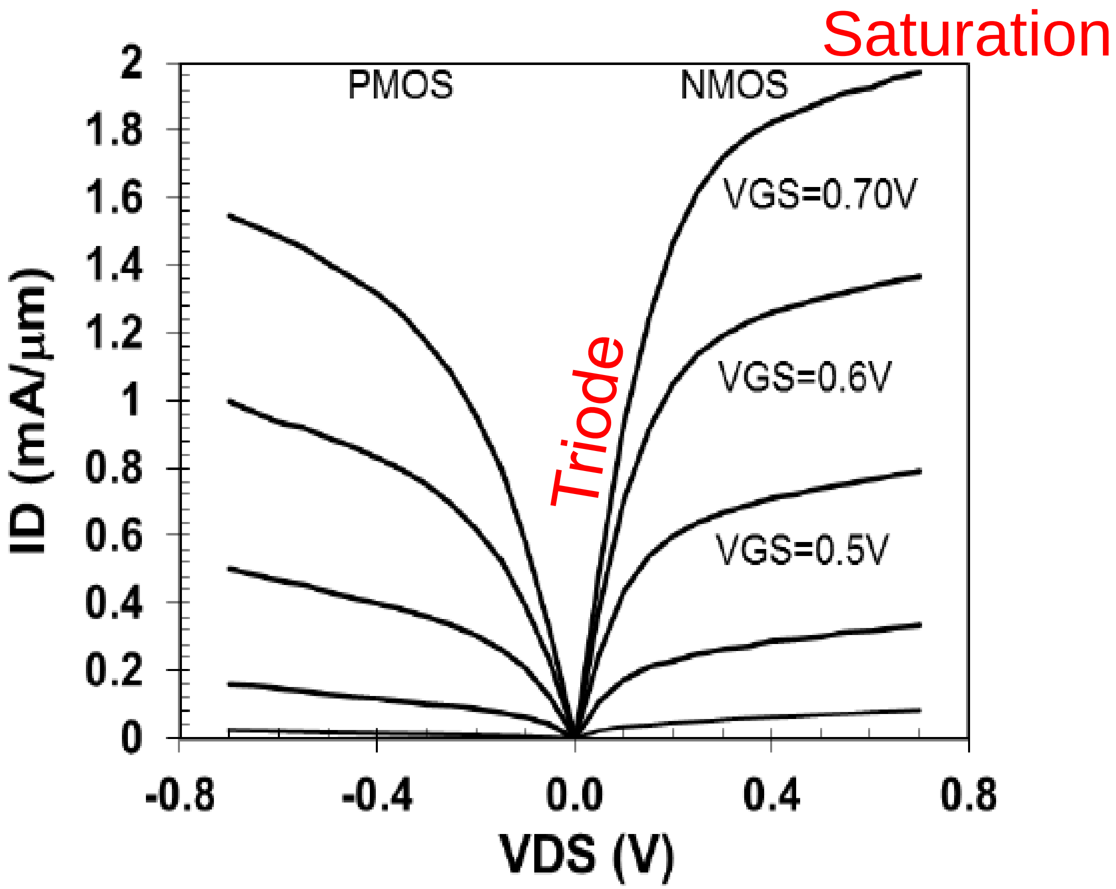
  – What happens when $V(x) = V_G - V_{TH}$?



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

State-of-the-art MOSFET (1)

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



State-of-the-art MOSFET (2)

- G. Yeap et al. (TSMC, IEDM 2019)
  - $I_D - V_G$ curves (NMOSFET & PMOSFET)

Log scale