VLSI Devices
Lecture 14

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The second half

- Two YouTube lectures (L25 & L26). Final exam on June 16 (maybe)

Coverage

- Two YouTube lectures reserved for advanced topics
  - L14: Substrate bias, channel mobility
  - L15: 3.2.1
  - L16: 3.2.1 (Continued)
  - L17: Velocity saturation (3.2.2)
  - L18: Channel length modulation and so on (3.2.3, 3.2.4, 3.2.5)
  - L19: MOSFET scaling
  - L20: MOSFET scaling (Continued)
  - L21: Quantum effect (4.2.4)
  - L22: Double-gate MOSFETs (10.3)
  - L23: FinFETs
  - L24: CFETs

Subthreshold slope (1)

- I_d is independent of V_{ds}, when $V_{ds} \gg k_B T/q$.

$$I_d = \mu_{eff} \frac{W}{L} \sqrt{\frac{\epsilon_{si} q N_a}{2\phi_s}} \left(\frac{k_B T}{q}\right)^2 \exp\left(\frac{q(V_{gs} - V_t)}{m k_B T}\right)$$

  - Its gate voltage dependence is very important.

$$\log_{10} I_d = (a\ constant) + \frac{q(V_{gs} - V_t)}{m k_B T} \log_{10} e$$

$$\frac{d(\log_{10} I_d)}{dV_{gs}} = \frac{q}{m k_B T} \log_{10} e$$

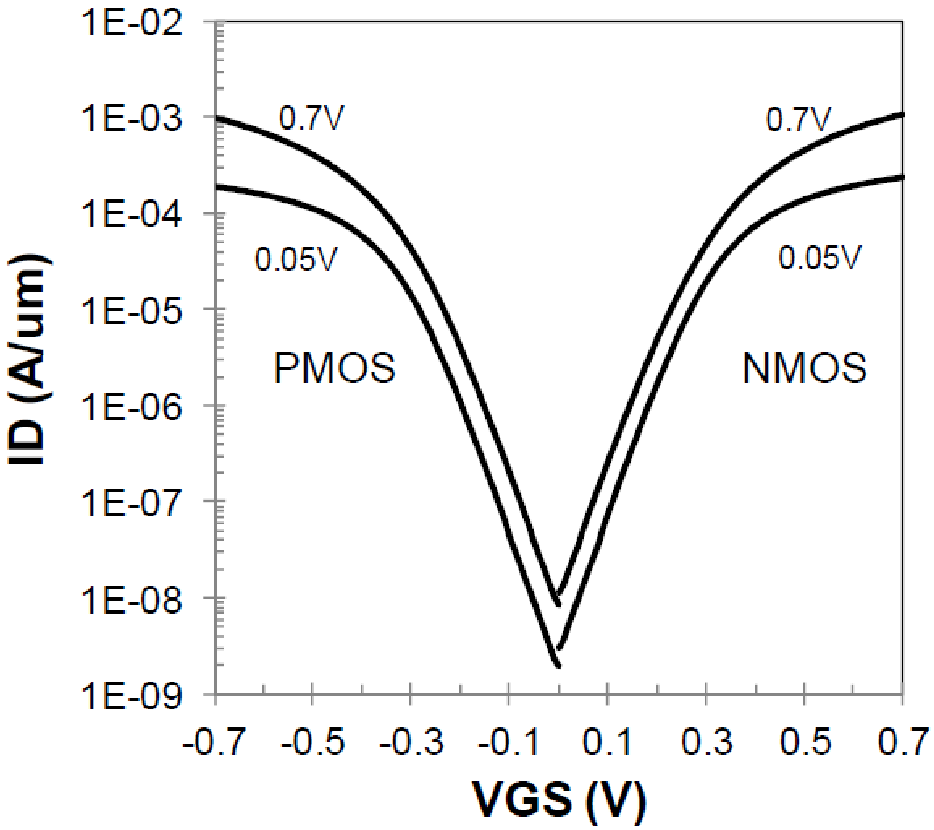
Subthreshold slope

$$S = \left(\frac{d(\log_{10} I_d)}{dV_{gs}}\right)^{-1} = \frac{m k_B T}{q} \ln 10$$

Taur, Eq. (3.41)

Subthreshold slope (2)

- At 300 K, $\frac{k_B T}{q} \ln 10$ is 60 mV/dec.
  - Note that m is larger than 1.



Subthreshold behavior
(Natarajan, IEDM 2024)

Substrate bias (1)

- Assume that the substrate is biased with V_{bs}. (For NMOSFETs, $V_{bs} < 0$)
  - Recall that ($\frac{dV}{d\phi_s} \approx 1$)

$$I_d \approx \mu_{eff} \frac{W}{L} \left\{ C_{ox}\left(V_{gs} - V_{fb}\right)\phi_s - \frac{1}{2} C_{ox}\phi_s^2 - \frac{2}{3}\sqrt{2\epsilon_{si} q N_a}\,\phi_s^{1.5} \right\}\Bigg|_{\phi_{s,s}}^{\phi_{s,d}}$$

  - Use $V_{gs} \Rightarrow V_{gs} - V_{bs}$, $\phi_{s,s} \Rightarrow 2\phi_B - V_{bs}$, and $\phi_{s,d} \Rightarrow 2\phi_B - V_{bs} + V_{ds}$.

Substrate bias (2)

- Then, we have

$$I_d = \mu_{eff}\frac{W}{L}\left[C_{ox}\left(V_{gs} - V_{fb} - 2\phi_B - \frac{1}{2}V_{ds}\right)V_{ds} - \frac{2}{3}\sqrt{2\epsilon_{si}qN_a}(2\phi_B - V_{bs} + V_{ds})^{1.5} + \frac{2}{3}\sqrt{2\epsilon_{si}qN_a}(2\phi_B - V_{bs})^{1.5}\right]$$

Taur, Eq. (3.43)

  – First-order expansion yields

$$I_d = \mu_{eff}\frac{W}{L}\left[C_{ox}\left(V_{gs} - V_{fb} - 2\phi_B\right) - \sqrt{2\epsilon_{si}qN_a}(2\phi_B - V_{bs})^{0.5}\right]V_{ds}$$

Substrate bias (3)

- Therefore, at low drain voltages,

$$I_d = \mu_{eff} C_{ox} \frac{W}{L} \left[\left(V_{gs} - V_{fb} - 2\phi_B \right) - \frac{1}{C_{ox}} \sqrt{2\epsilon_{si} q N_a (2\phi_B - V_{bs})} \right] V_{ds}$$

  - It means that

$$V_t = V_{fb} + 2\phi_B + \frac{\sqrt{2\epsilon_{si} q N_a (2\phi_B - V_{bs})}}{C_{ox}}$$

Taur, Eq. (3.44)

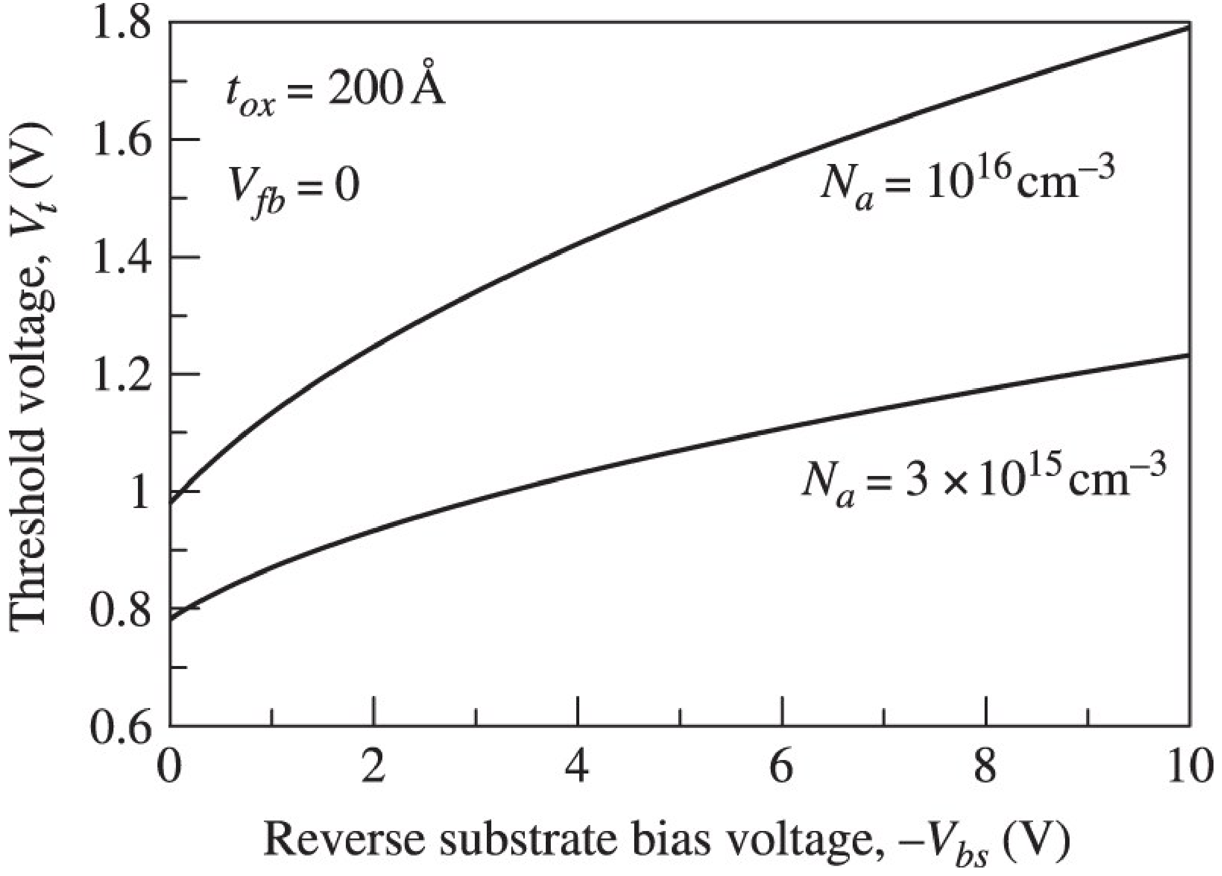
  - Substrate sensitivity

$$\frac{dV_t}{d(-V_{bs})} = \frac{\sqrt{\epsilon_{si} q N_a}}{C_{ox}\sqrt{2(2\phi_B - V_{bs})}}$$

Taur, Eq. (3.45)

Substrate bias (4)

- A reverse substrate bias is to widen the bulk depletion region and raise the threshold voltage.



Threshold voltage variation with reverse substrate bias for two uniform substrate doping concentration (Taur, Fig. 3.14)

Effective mobility

- Previously, we made the following simplification:

$$I_d(y) = qW \int_0^{x_i} \mu_n n(x,y) \frac{dV}{dy} dx = -\mu_{eff} W \frac{dV}{dy} \left(-q \int_0^{x_i} n(x,y) dx \right)$$

$$= -\mu_{eff} W \frac{dV}{dy} Q_i(y)$$

Taur, Eq. (3.8)

  - Then, what is μ_{eff}?

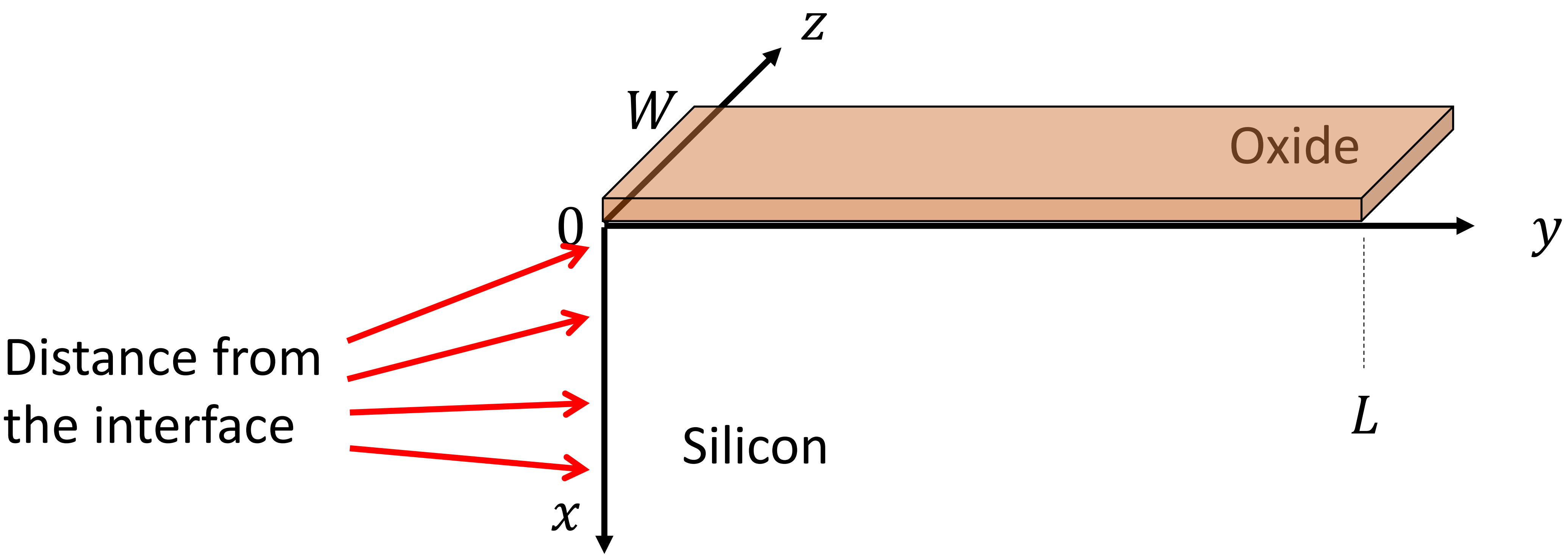
$$\mu_{eff}(y) = \frac{\int_0^{x_i} \mu_n n(x,y) dx}{\int_0^{x_i} n(x,y) dx}$$

Taur, Eq. (3.50)

Position-dependent

Why is the mobility position-dependent?

- In addition to the bulk scattering mechanisms,
  - Additional scattering mechanisms are important.



Effective mobility against effective field

- Effective field
  - Average electric field perpendicular to the Si-SiO_2 interface experienced by the carriers in the channel

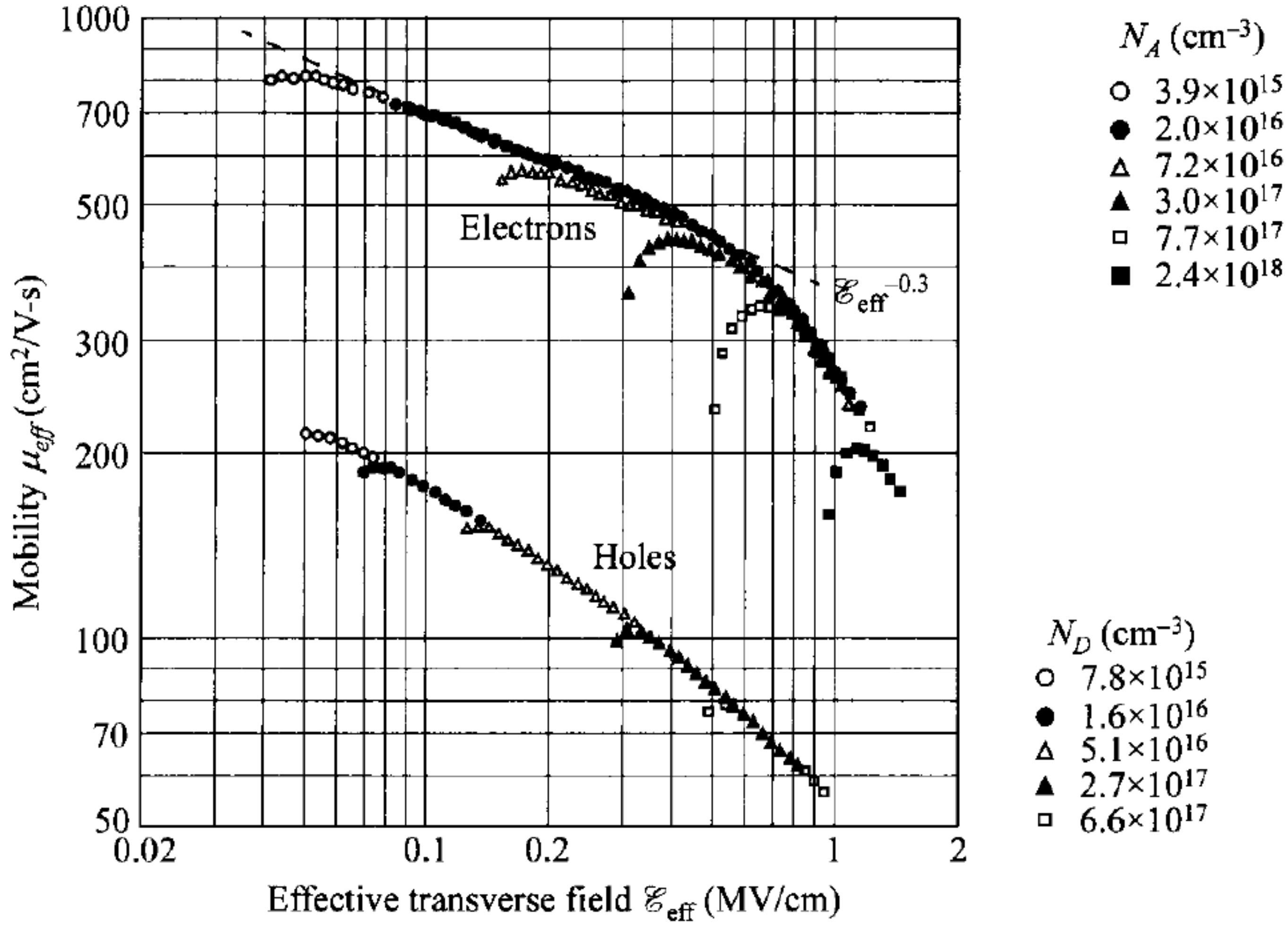
$$\mathcal{E}_{eff} = \frac{1}{\epsilon_{si}}\left(|Q_d| + \frac{1}{2}|Q_i|\right) \qquad \text{Taur, Eq. (3.51)}$$

  - Using $|Q_d| \approx C_{ox}(V_t - V_{fb} - 2\phi_B)$ and $|Q_i| \approx C_{ox}(V_{gs} - V_t)$,

$$\mathcal{E}_{eff} = \frac{V_t - V_{fb} - 2\phi_B}{3t_{ox}} + \frac{V_{gs} - V_t}{6t_{ox}} \qquad \text{Taur, Eq. (3.53)}$$

Mobility variation

- Mobility variation (Vertical field dependence)



Inversion-layer mobility (Sze’s book)

Thank you!