Lecture11:
Physics of MOS transistors (3)

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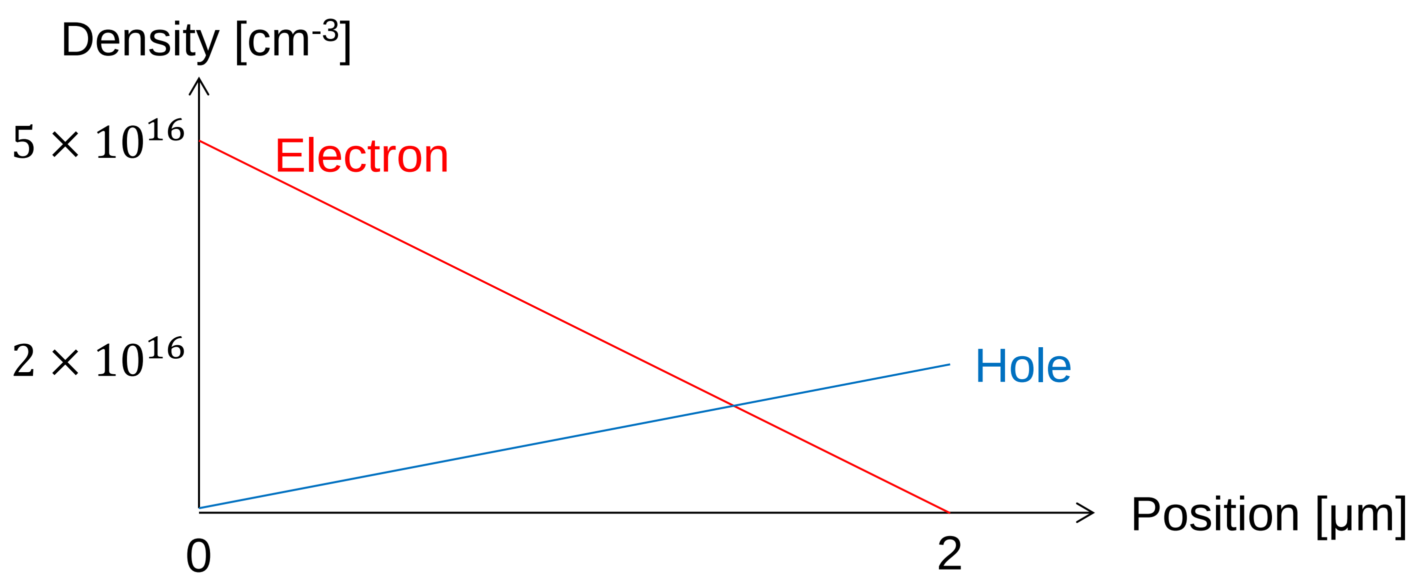
Homework#1-1

- Problem1:
  - Consider three semiconductor materials, Si, Ge, and GaAs. Find the values of the intrinsic carrier density (at 300K) and the band gap energy. Specify the reference of values.
- Answer:
  - Si: 4.6×10^{9} cm^{-3}, 1.11eV
  - Ge: 1.7×10^{13} cm^{-3}, 0.66 eV
  - GaAs: 2.6×10^{6} cm^{-3}, 1.43 eV
  - Reference: Kittel, Introduction to Solid State Physics, 7th edition.
- Comments:
  - Different references show considerably different values!
  - You cannot use (2.1) for Ge or GaAs!

Homework#1-2 (1/2)

- Problem2:
  - The figure shows a p-type bar of silicon that is subjected to electron injection from the left and hole injection from the right. Determine the total current flowing through the device if the cross section area is equal to 1 μm X 1 μm.



Homework#1-2 (2/2)

- Answer:
  - The electron diffusion current density

$$J_n = +qD_n \frac{dn}{dx} = -1.4 \times 10^3\ \mathrm{A/cm^2} \quad \leftarrow 1350\ \mathrm{cm^2/V/sec}$$

  - The hole diffusion current density

$$J_p = -qD_p \frac{dp}{dx} = -0.2 \times 10^3\ \mathrm{A/cm^2} \quad \leftarrow 480\ \mathrm{cm^2/V/sec}$$

  - Total current is $-1.6 \times 10^{-5}\mathrm{A}$.
- Comments:
  - Direction?
  - Unit conversion?

Homework#1-3

- Problem3:
  - A junction employs $N_D = 5 \times 10^{17}$ /cm³ and $N_A = 4 \times 10^{16}$ /cm³. Consider three different temperatures, 250 K, 300 K, 350 K. For these cases, determine the majority and minority carrier concentration on both sides. Also calculate the built-in potential.
- Answer:
  - Majority carrier density is 5×10^{17} /cm³ and 4×10^{16} /cm³, respectively.

	n_i [cm⁻³]	n-type minor. [cm⁻³]	p-type minor. [cm⁻³]	Built-in potential [V]
250K	1.1×10^{8}	2.4×10^{-2}	3.0×10^{-1}	0.90
300K	1.1×10^{10}	2.4×10^{2}	3.0×10^{3}	0.85
350K	3.0×10^{11}	1.8×10^{5}	2.3×10^{6}	0.79

Homework#1-4

- Problem4:
  - In the textbook, you can find a derivation of the built-in potential formula:

$$V_0 = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$

  - Derive the above formula with your own effort.
- Answer:
  - See p. 27

Homework#1-5 (1/2)

- Problem5:
  - Consider a pn junction at equilibrium.
  - Show that the width of the depletion region is given by:

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$$

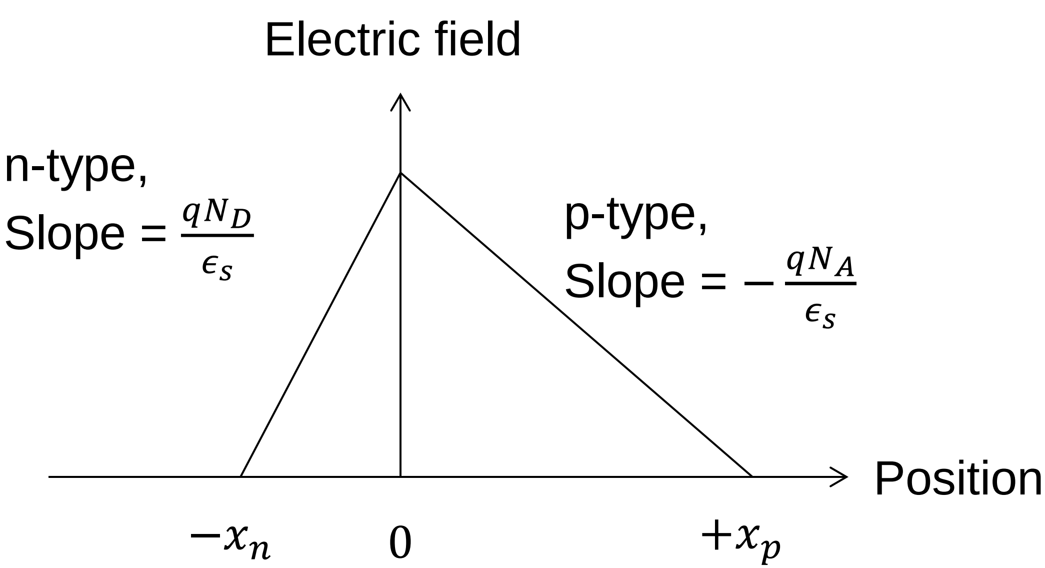
  - Show that the charge stored in a pn junction is given by:

$$Q = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D} V_0}$$

  - (This problem can be a bit challenging.)

Homework#1-5 (2/2)

- Answer:



← $N_D x_n = N_A x_p$

← The total area must be V_0.

– From the above graph, it is found that

$$x_n = \sqrt{\frac{1}{q}\frac{2\epsilon_s V_0}{N_A+N_D}\frac{N_A}{N_D}} \text{ and } x_p = \sqrt{\frac{1}{q}\frac{2\epsilon_s V_0}{N_A+N_D}\frac{N_D}{N_A}}$$

Derivation of IV (1/2)

- Drain current
  - First of all, the current is given by

$$I = Q\ v \tag{6.4}$$

  - Here, Q is the charge density *per unit length*.
  - It follows

$$Q = WC_{ox}[V_G - V(x) - V_{TH}] \tag{6.3}$$

  - Also v is the electron velocity.

$$v = -\mu_n E = +\mu_n \frac{dV}{dx} \tag{6.5 and 6.6}$$

  - The drain current is

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

Derivation of IV (2/2)

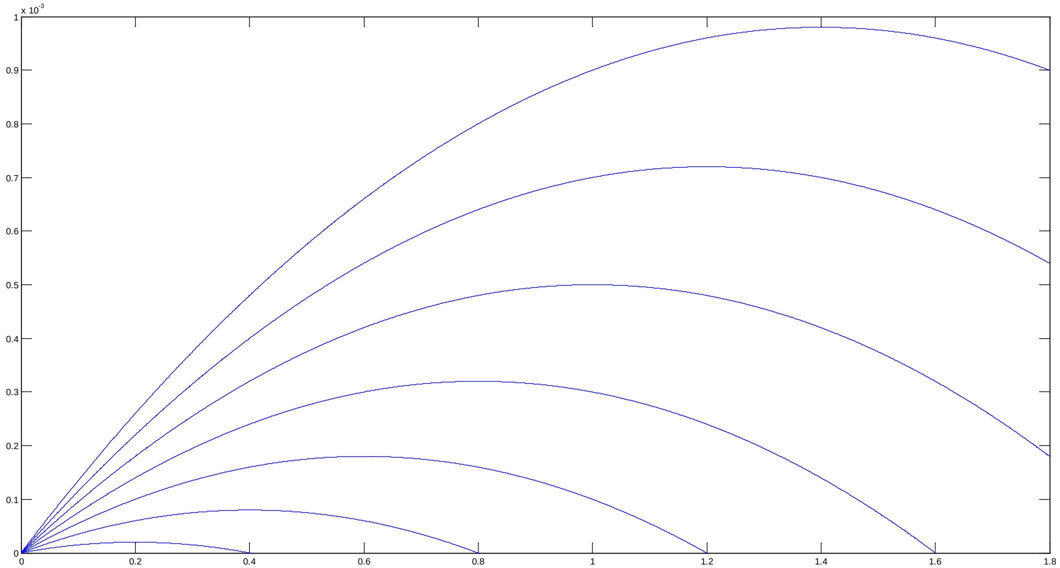
- Integration over the channel
  - Simply re-arranging,

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

  - When integrated,

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

Current



Voltage

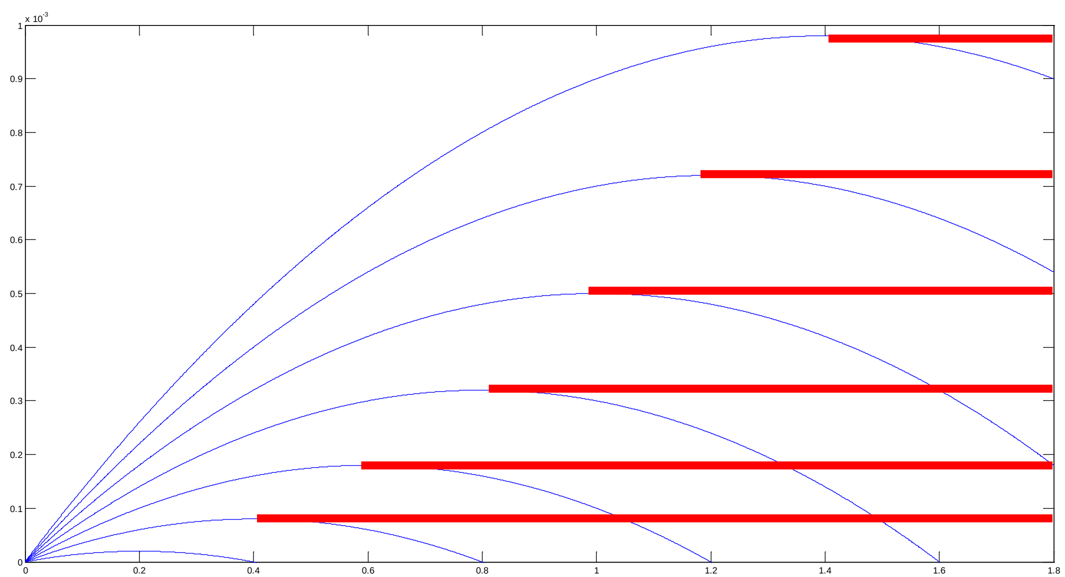
🡐 Is it acceptable?

Of course, not!

- Current usually increases as the voltage increases…
- Recall (6.3).

$$Q = WC_{ox}[V_G - V(x) - V_{TH}] \quad (6.3)$$

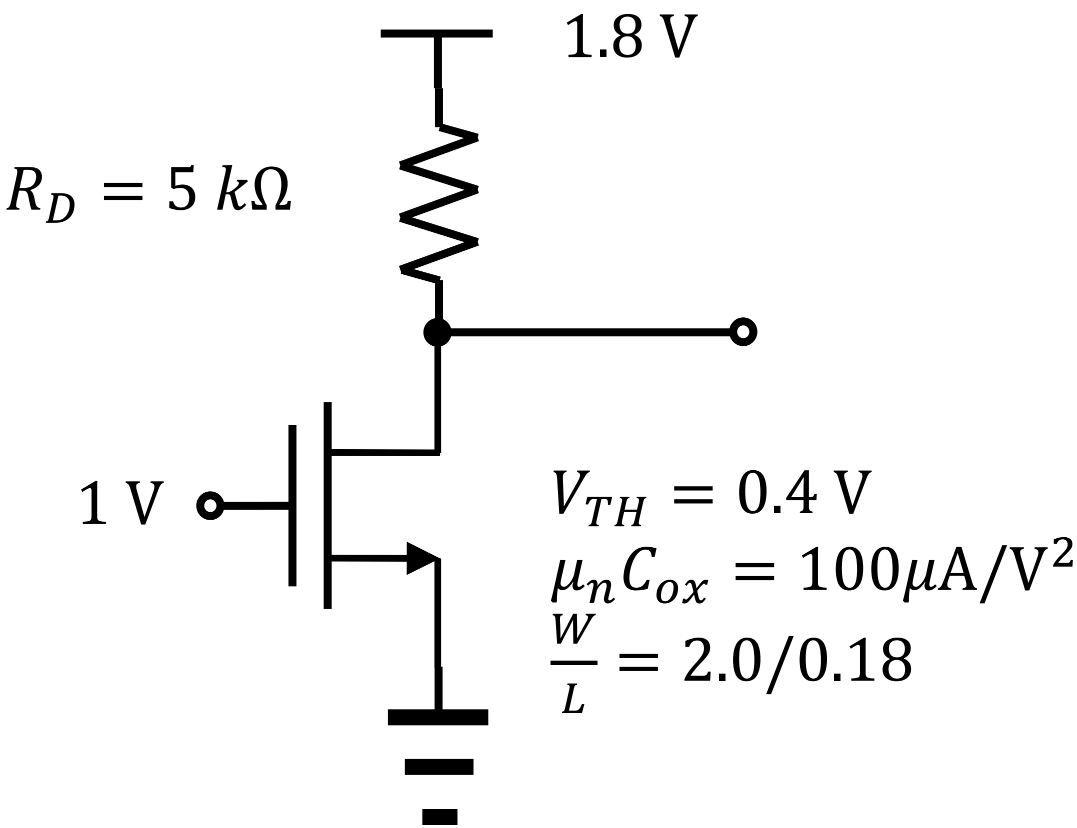
  – What happens when $V(x) = V_G - V_{TH}$?
  – “Saturation region”



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

Example 6.6

- Assume the saturation region.
  - Then, the saturation current becomes $200\ \mu\mathrm{A}$.

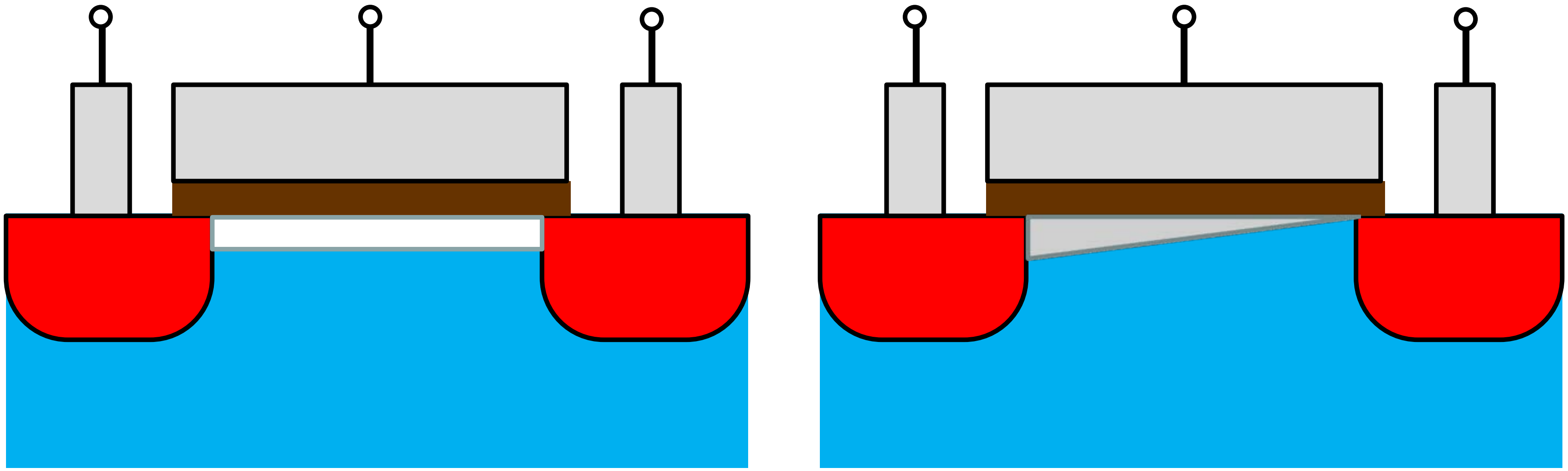


Long vs. short

- Long channel device
  - “Long”?
  - It depends on the situation.
- Short channel device
  - “Short”?
  - Again, it depends on the situation.
- Channel-length modulation
- Velocity saturation
- Body effect

Channel length modulation

- Channel length modulation



- Output resistance?

$$r_O = \frac{\Delta V_{DS}}{\Delta I_D}$$

MOS transconductance

- "conductance" of a simple resistor
  - It means $\frac{I}{V}$.
- "trans" + "conductance"
  - Between different terminals

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \quad (6.44)$$

  - For the saturation region,

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})$$

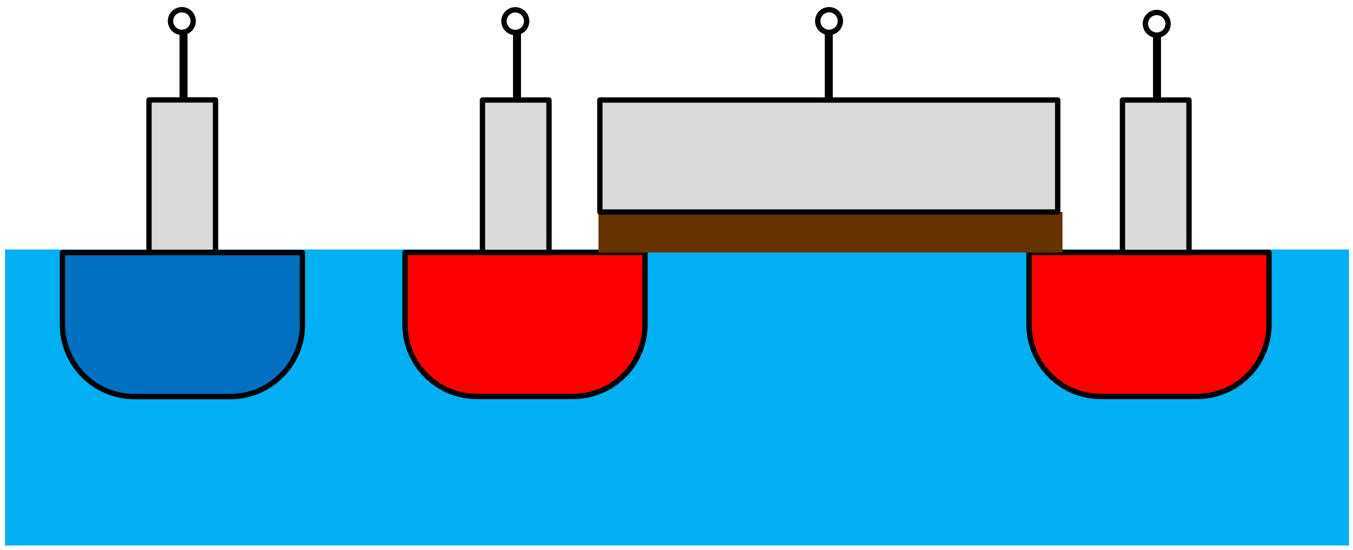
🡐 Why?

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}}$$

Body effect

- Actually, a MOSFET is a four-terminal device.
  - Substrate (or bulk)
  - Threshold voltage, V_{TH}, varies. (In which direction?)



Two more issues

- Velocity saturation
  - Once again, the current is given by

$$I = Q\ v \tag{6.4}$$

  - How did we have the saturation?

- Subthreshold conduction
  - Although not covered, it's the critical issue!

Summary

- “Everything studied in this lecture is important.”
  - Hmmm…

- My suggestion
  - Try to understand them.
  - Remember the IV characteristics.

Read your textbook!

- Today, we studied the short-channel effect of the MOSFET.
  - Up to p. 267
- In the Lecture12, we will cover the remaining parts of Ch. 6.
  - Small-signal model
  - CMOS technology
  - Up to. 273