VE320 Intro to Semiconductor Devices Summer 2022 — Problem Set 9

July 31, 2022

Exercise 9.1

Assume that the subthreshold current of a MOSFET is given by

$$I_D = 10^{-15} \exp\left(\frac{V_{GS}}{(2.1)V_t}\right)$$

over the range $0 \leq V_{GS} \leq 1$ volt and where the factor 2.1 takes into account the effect of interface states. Assume that 10^6 identical transistors on a chip are all biased at the same V_{GS} and at $V_{DD} = 5$ V.

(a) Calculate the total current that must be supplied to the chip at $V_{GS} = 0.5, 0.7$, and 0.9 V.

(b) Calculate the total power dissipated in the chip for the same V_{GS} values.

Answer:

(a)

$$I_D = 10^{-15} \exp\left(\frac{V_{GS}}{(2.1)V_t}\right)$$

For $V_{GS} = 0.5$ V,

$$\begin{aligned}
& I_D = 10^{-15} \exp\left[\frac{0.5}{(2.1)(0.0259)}\right] \Rightarrow \\
& I_D = 9.83 \times 10^{-12} \text{ A} \\
& \text{For } V_{GS} = 0.7 \text{ V}, \\
& I_D = 3.88 \times 10^{-10} \text{ A} \\
& \text{For } V_{GS} = 0.9 \text{ V}, \\
& I_D = 1.54 \times 10^{-8} \text{ A} \\
& \text{Then the total current is:} \\
& I_T = I_D\left(10^6\right) \\
& \text{For } V_{GS} = 0.5 \text{ V}, I_T = 9.83 \mu\text{A} \\
& \text{For } V_{GS} = 0.7 \text{ V}, I_T = 0.388 \text{ mA} \\
& \text{For } V_{GS} = 0.9 \text{ V}, I_T = 15.4 \text{ mA} \\
& \text{(b)} \\
& \text{Power: } P = I_T \cdot V_{DD} \\
& \text{Then} \\
& \text{For } V_{GS} = 0.5 \text{ V}, P = 49.2 \mu\text{W} \\
& \text{For } V_{GS} = 0.7 \text{ V}, P = 1.94 \text{ mW} \\
& \text{For } V_{GS} = 0.9 \text{ V}, P = 77 \text{ mW}
\end{aligned}$$

Exercise 9.2

A silicon MOSFET has parameters $N_a = 4 \times 10^{16}\ \mathrm{cm}^{-3}, t_{ox} = 12\ \mathrm{nm} = 120\mathring{A}$, $Q'_{ss} = 4 \times 10^{10}\ \mathrm{cm}^{-2}$, and $\phi_{ms} = -0.5$ V. The transistor is biased at $V_{GS} = 1.25$ V and $V_{SB} = 0$.

(a) Calculate ΔL for (i) $\Delta V_{DS} = 1$ V, (ii) $\Delta V_{DS} = 2$ V, and (iii) $\Delta V_{DS} = 4$ V.

(b) Determine the minimum channel length L such that $\Delta L/L = 0.12$ for $V_{GS} = 1.25$ V and $\Delta V_{DS} = 4$ V.

Answer:

$$\begin{aligned} C_{ox} &= \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)\left(8.85 \times 10^{-14}\right)}{120 \times 10^{-8}} \\ &= 2.876 \times 10^{-7}\ \mathrm{F/cm}^2 \\ V_{FB} &= \phi_{ms} - \frac{Q'_{ss}}{C_{ox}} \\ &= -0.5 - \frac{\left(4 \times 10^{10}\right)\left(1.6 \times 10^{-19}\right)}{2.876 \times 10^{-7}} \\ V_{FB} &= -0.5223\ \mathrm{V} \end{aligned}$$

Now

$$V_T = \frac{|Q'_{SD}(\max)|}{C_{\alpha x}} + V_{FB} + 2\phi_{fp}$$

We find

$$\begin{aligned} \phi_{fp} &= (0.0259)\ln\left(\frac{4 \times 10^{16}}{1.5 \times 10^{10}}\right) = 0.3832\ \mathrm{V} \\ x_{dT} &= \left[\frac{4(11.7)\left(8.85 \times 10^{-14}\right)(0.3832)}{\left(1.6 \times 10^{-19}\right)\left(4 \times 10^{16}\right)}\right]^{1/2} \\ &= 1.575 \times 10^{-5}\ \mathrm{cm} \\ &|Q'_{SD}(\max)| \\ &= \left(1.6 \times 10^{-19}\right)\left(4 \times 10^{16}\right)\left(1.575 \times 10^{-5}\right) \\ &= 1.008 \times 10^{-7}\mathrm{C/cm}^2 \end{aligned}$$

So

$$\begin{aligned} V_T &= \frac{1.008 \times 10^{-7}}{2.876 \times 10^{-7}} - 0.5223 + 2(0.3832) \\ &= 0.595\ \mathrm{V} \\ V_{DS}(\text{ sat }) &= V_{GS} - V_T = 1.25 - 0.595 = 0.655\ \mathrm{V} \\ \sqrt{\frac{2\epsilon_s}{eN_a}} &= \sqrt{\frac{2(11.7)\left(8.85 \times 10^{-14}\right)}{\left(1.6 \times 10^{-19}\right)\left(4 \times 10^{16}\right)}} \\ &= 1.799 \times 10^{-5}\ \mathrm{cm/V}^{1/2} \end{aligned}$$

(a) $\Delta L = \sqrt{\frac{2\epsilon_s}{eN_a}}\left[\sqrt{\phi_{fp} + V_{DS}(sat) + \Delta V_{DS}}\right.$

$$\left. - \sqrt{\phi_{fp} + V_{DS}(sat)}\right]$$

(i)

$$\begin{aligned} \Delta L &= \left(1.799 \times 10^{-5}\right) \\ &\times [\sqrt{0.3832 + 0.655 + 1} - \sqrt{0.3832 + 0.655}] \\ \Delta L &= 7.35 \times 10^{-6}\ \mathrm{cm} = 0.0735\mu\mathrm{m} \end{aligned}$$

(ii)

$$\Delta L = \left(1.799 \times 10^{-5}\right)$$
$$\times \left[\sqrt{0.3832 + 0.655 + 2} - \sqrt{0.3832 + 0.655}\right]$$
$$\Delta L = 1.303 \times 10^{-5} \text{ cm} = 0.1303\mu\text{m}$$

(iii)

$$\Delta L = \left(1.799 \times 10^{-5}\right)$$
$$\times \left[\sqrt{0.3832 + 0.655 + 4} - \sqrt{0.3832 + 0.655}\right]$$
$$\Delta L = 2.205 \times 10^{-5} \text{ cm} = 0.2205\mu\text{m}$$

(b)

$$\frac{\Delta L}{L} = 0.12 = \frac{0.2205}{L}$$
$$L = 1.84\mu\text{m}$$

Exercise 9.3

Consider an n-channel silicon MOSFET. The parameters are $k'_n = 75\mu\text{A/V}^2$, $W/L = 10$, and $V_T = 0.35$ V. The applied drain-to-source voltage is $V_{DS} = 1.5$ V.

(a) For $V_{GS} = 0.8$ V, find (i) the ideal drain current, (ii) the drain current if $\lambda = 0.02\ \text{V}^{-1}$, and (iii) the output resistance for $\lambda = 0.02\ \text{V}^{-1}$.

(b) Repeat part (a) for $V_{GS} = 1.25$ V.

Answer:

(a)

(i)

$$I_D = \frac{k'_n}{2} \cdot \frac{W}{L} \left(V_{GS} - V_T\right)^2$$
$$= \left(\frac{0.075}{2}\right)(10)(0.8 - 0.35)^2$$
$$= 0.07594 \text{ mA} = 75.94\mu\text{A}$$

(ii)

$$I'_D = I_D \left(1 + \lambda V_{DS}\right)$$
$$= (75.9375)[1 + (0.02)(1.5)]$$
$$= 78.22\mu\text{A}$$

(iii)

$$r_o = \frac{1}{\lambda I_D} = \frac{1}{(0.02)(75.94)}$$
$$= 0.658\text{M}\Omega = 658\text{k}\Omega$$

(b)

(i)

$$I_D = \left(\frac{0.075}{2}\right)(10)(1.25 - 0.35)^2$$
$$= 0.30375 \text{ mA}$$

(ii)

$$I'_D = (0.30375)[1 + (0.02)(1.5)]$$

$$= 0.3129 \text{ mA}$$

(iii)

$$r_o = \frac{1}{(0.02)(0.30375)} = 165\text{k}\Omega$$

Exercise 9.4

(a) What is subthreshold conduction? Sketch a drain current versus gate voltage plot that shows the subthreshold current for the transistor biased in the saturation region.

(b) What is channel length modulation? Sketch an I–V curve that shows the channel length modulation effect.

(c) What is velocity saturation and what is its effect on the I–V relation of a MOSFET?

(d) Sketch the space charge region in the channel of a short-channel MOSFET and show the charge-sharing effect. Why does the threshold voltage decrease in a short-channel NMOS device?

Answer:

(a)

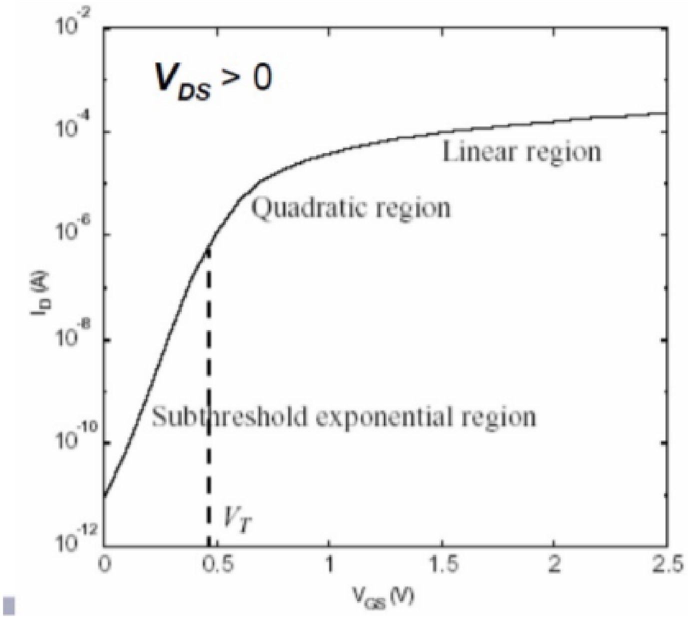

Figure 1: Figure for Problem 9.4

(b)

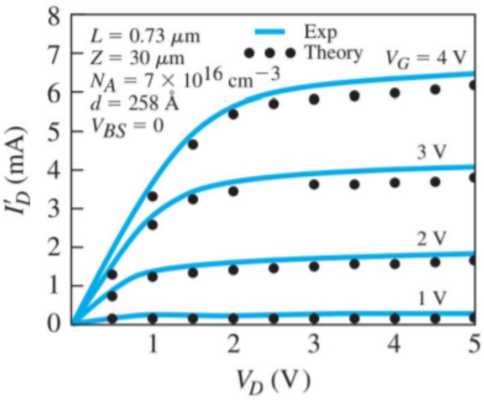

Figure 2: Figure for Problem 9.4

(c)

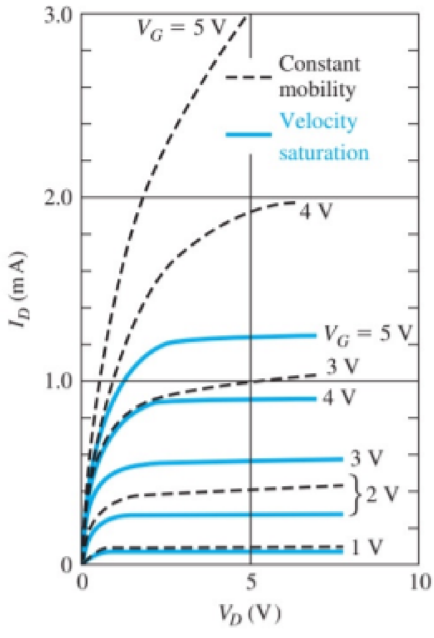

Figure 3: Figure for Problem 9.4

(d)

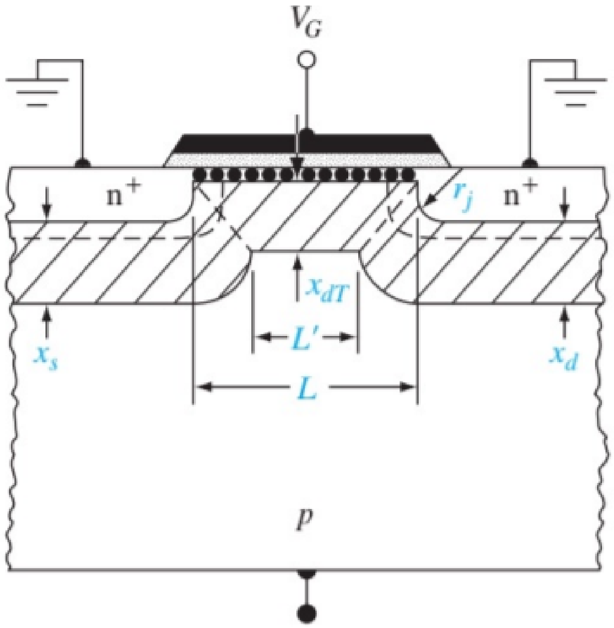

Figure 4: Figure for Problem 9.4

Exercise 9.5

For a uniformly doped $n^{++}p^{+}n$ bipolar transistor in thermal equilibrium,
(a) sketch the energy-band diagram
(b) sketch the electric field through the device
(c) repeat parts (a) and (b) for the transistor biased in the forward-active region.

Answer:

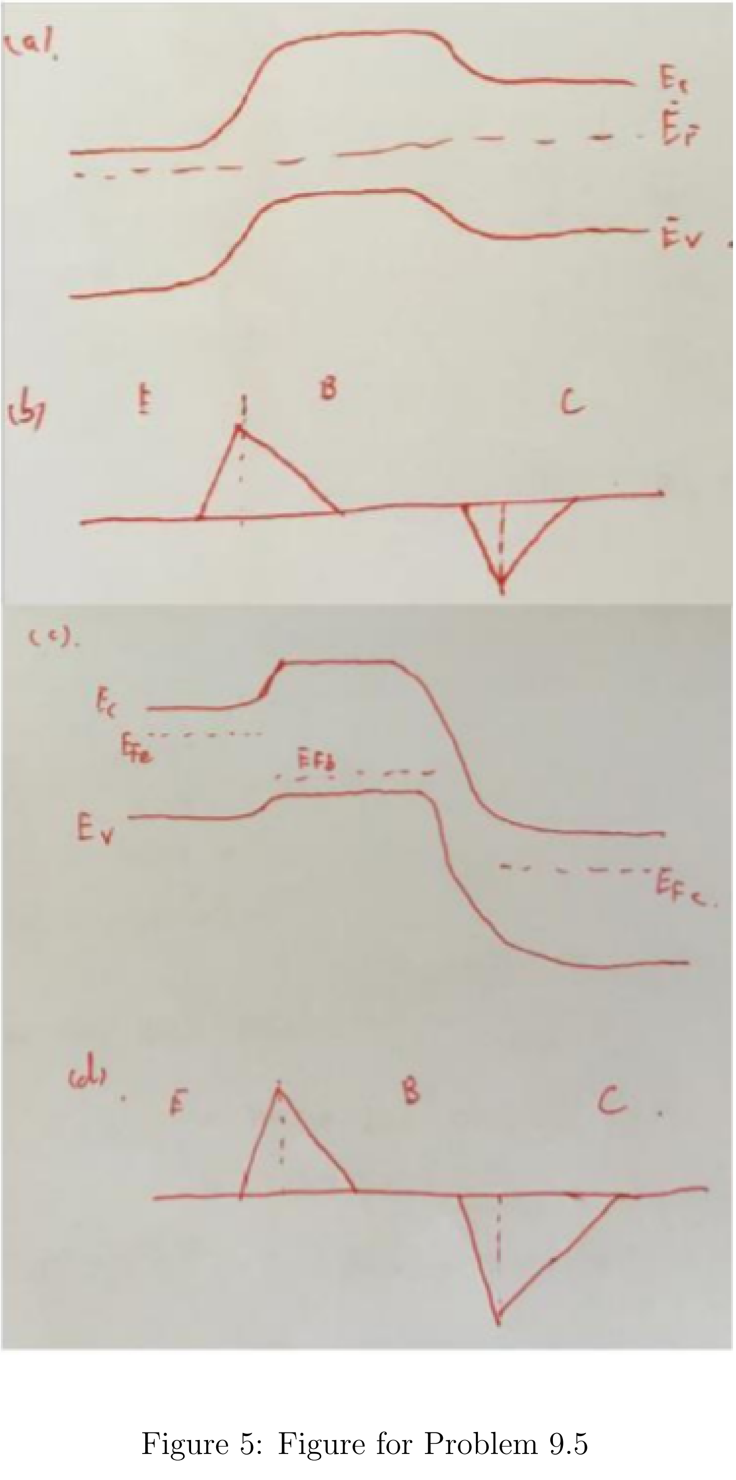

Figure 5: Figure for Problem 9.5

Exercise 9.6

What is Early effect? How to minimize it?

Answer:

Early Effect: As V_c becomes larger, the base-collector is more reverse-biased, then the depletion region becomes larger and extends more into the base region. Hence electrons are more likely to be swept into the collector. resulting in a higher gain. To minimize it, we can make doping concentration in the base larger than that in the collector, so that the depletion region in the base s small.

Exercise 9.7

(a) From fabrication point of view, why is Si the most commonly used material in semiconductor industry nowadays?

(b) After this course, what did you learn about semiconductors?

Answer:

(a)1. Si is easy to get (e.g. from sand) less expensive

2. Si has big bandgap, so that it could be operated in high temperature and has less leakage current.

3. SiO_2 can protect Si

(b) Chapter 1: The Crystal Structure of Solids

Chapter 2: Introduction to Quantum Mechanics

Chapter 3: Introduction to the Quantum Theory of Solids

Chapter 4: The Semiconductor in Equilibrium

Chapter 5: Carrier Transport Phenomena

Chapter 6: Nonequilibrium Excess Carriers in Semiconductors

Chapter 7: The pn Junction

Chapter 8: The pn Junction Diode

Chapter 9: Metal–Semiconductor and Semiconductor Heterojunctions

Chapter 10: Fundamentals of the Metal–Oxide– Semiconductor Field-Effect Transistor

Chapter 11: Metal–Oxide–Semiconductor Field-Effect Transistor: Additional Concepts

Chapter 12: The Bipolar Transistor

Reference

1. Neamen, Donald A. Semiconductor physics and devices: basic principles. McGraw-hill, 2003.