VE320 Intro to Semiconductor Devices
Summer 2022 — Problem Set 8

July 31, 2022

Exercise 8.1

The high-frequency $C-V$ characteristic curve of a MOS capacitor is shown in Figure 1. The area of the device is 2×10^{-3} cm^2. The metal-semiconductor work function difference is $\phi_{ms} = -0.50$ V, the oxide is SiO_2, the semiconductor is silicon, and the semiconductor doping concentration is 2×10^{16} cm^{-3}.

(a) Is the semiconductor n or p type?
(b) What is the oxide thickness?
(c) What is the equivalent trapped oxide charge density?
(d) Determine the flat-band capacitance.

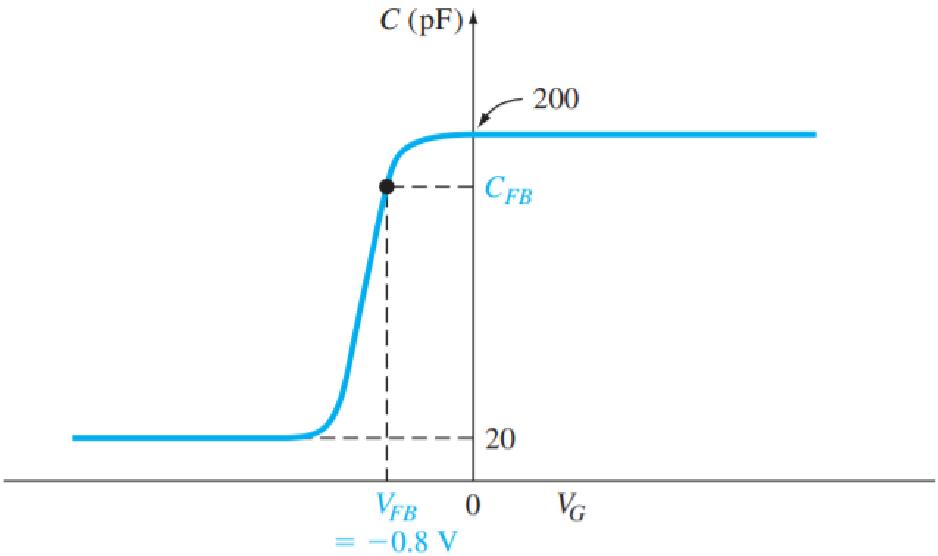


Figure 1: Figure for Problem 8.1

Answer:
(a) n-type
(b) We have

$$C_{ox} = \frac{200 \times 10^{-12}}{2 \times 10^{-3}} = 1 \times 10^{-7} \text{ F/cm}^2$$

Also

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \Rightarrow t_{ox} = \frac{\in_{ox}}{C_{ox}} = \frac{(3.9)\left(8.85 \times 10^{-14}\right)}{1 \times 10^{-7}}$$

or

$$t_{ox} = 3.45 \times 10^{-6} \text{ cm} = 34.5 \text{ nm} = 345^{\circ} A$$

(c)

$$V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}$$

or

$$-0.80 = -0.50 - \frac{Q'_{ss}}{10^{-7}}$$

which yields

$$Q'_{ss} = 3 \times 10^{-8}\mathrm{C/cm^2} = 1.875 \times 10^{11}\ \mathrm{cm^{-2}}$$

(d)

$$C'_{FB} = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right)\sqrt{\left(\frac{kT}{e}\right)\left(\frac{\epsilon_s}{eN_d}\right)}}$$

$$= \left[(3.9)\left(8.85 \times 10^{-14}\right)\right] \boldsymbol{\nabla} \cdot \left[3.45 \times 10^{-6} + \left(\frac{3.9}{11.7}\right)\sqrt{\frac{(0.0259)(11.7)\left(8.85 \times 10^{-14}\right)}{\left(1.6 \times 10^{-19}\right)\left(2 \times 10^{16}\right)}}\right]$$

which yields

$$C'_{FB} = 7.82 \times 10^{-8}\ \mathrm{F/cm^2}$$

or

$$C_{FB} = 156\mathrm{pF}$$

Exercise 8.2

Consider the high-frequency $C - V$ plot shown in Figure 2.

(a) Indicate which points correspond to flat-band, inversion, accumulation, threshold, and depletion modes.

(b) Sketch the energy-band diagram in the semiconductor for each condition.

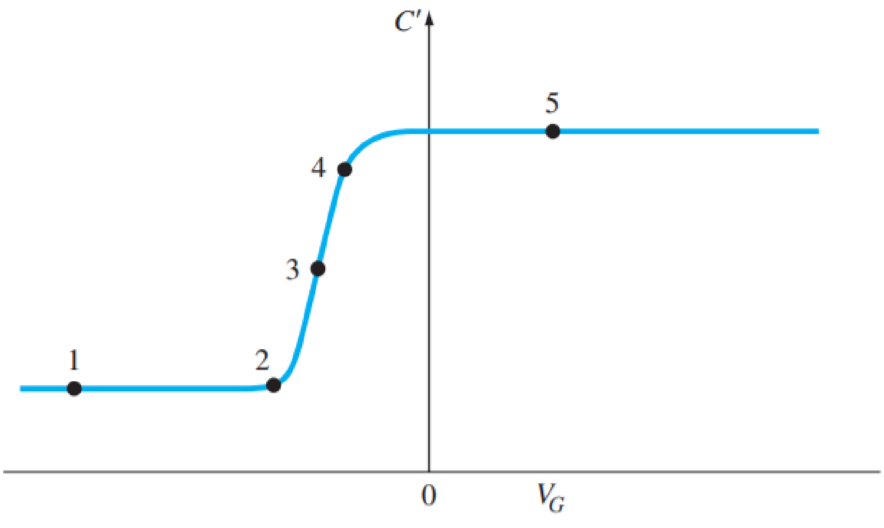


Figure 2: Figure for Problem 8.2

Answer:

(a)

Point 1: Inversion

2: Threshold

3: Depletion

4: Flat-band
5: Accumulation
(b)

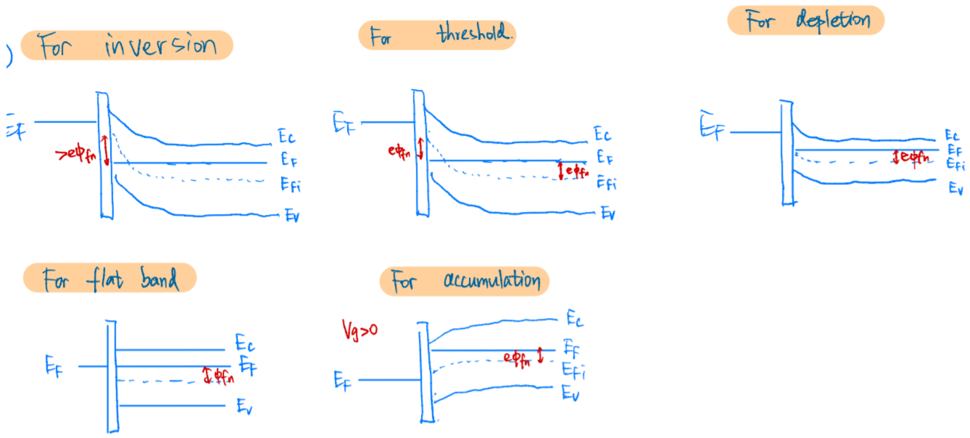


Figure 3: Figure for Problem 8.2

Exercise 8.3

A p-channel MOSFET has the following parameters: $k_p' = 0.10\ \mathrm{mA/V^2}, W/L = 15$, and $V_T = -0.4$ V. Calculate the drain current I_D for
(a) $V_{SG} = 0.8$ V, $V_{SD} = 0.25$ V;
(b) $V_{SG} = 0.8$ V, $V_{SD} = 1.0$ V ;
(c) $V_{SG} = 1.2$ V, $V_{SD} = 1.0$ V;
(d) $V_{SG} = 1.2$ V, $V_{SD} = 2.0$ V.

Answer:
(a) $I_D = \frac{k_p'}{2} \cdot \frac{W}{L}\left[2\left(V_{SG}+V_T\right)V_{SD} - V_{SD}^2\right] = \left(\frac{0.10}{2}\right)(15)\left[2(0.8-0.4)(0.25)-(0.25)^2\right]$

$$I_D = 0.103\ \mathrm{mA}$$

(b) $I_D = \frac{k_p'}{2} \cdot \frac{W}{L}\left(V_{SG}+V_T\right)^2 = \left(\frac{0.10}{2}\right)(15)(0.8-0.4)^2 = 0.12$ mA
(c)

$$\begin{aligned} I_D &= \frac{k_p'}{2} \cdot \frac{W}{L}\left(V_{SG}+V_T\right)^2 \\ &= \left(\frac{0.10}{2}\right)(15)(1.2-0.4)^2 \\ &= 0.48\ \mathrm{mA} \end{aligned}$$

(d) Same as (c), $I_D = 0.48$ mA

Exercise 8.4

Consider a p-channel MOSFET with the following parameters: $k_p' = 0.12\ \mathrm{mA/V^2}$ and $W/L = 20$. The drain current is 100μA with applied voltages of $V_{SG} = 0$, $V_{BS} = 0$, and $V_{SD} = 1.0$ V.
(a) Determine the V_T value.

(b) Determine the drain current I_D for $V_{SG} = 0.4$ V, $V_{SB} = 0$, and $V_{SD} = 1.5$ V.
(c) What is the value of I_D for $V_{SG} = 0.6$ V, $V_{SB} = 0$, and $V_{SD} = 0.15$ V?

Answer:
(a) Assume biased in saturation region

$$\begin{aligned} I_D &= \frac{k_p'}{2} \cdot \frac{W}{L} \left(V_{SG} + V_T\right)^2 \\ 0.10 &= \left(\frac{0.12}{2}\right)(20)\left(0 + V_T\right)^2 \\ &\Rightarrow V_T = +0.289 \text{ V} \end{aligned}$$

Note: $V_{SD} = 1.0 \text{ V} > V_{SG} + V_T = 0 + 0.289$ V So the transistor is biased in the saturation region.
(b)

$$\begin{aligned} I_D &= \left(\frac{0.12}{2}\right)(20)(0.4 + 0.289)^2 \\ &= 0.570 \text{ mA} \end{aligned}$$

(c)

$$\begin{aligned} I_D &= \left(\frac{0.12}{2}\right)(20)[2(0.6 + 0.289)(0.15) \\ &-(0.15)^2] \\ I_D &= 0.293 \text{ mA} \end{aligned}$$

Exercise 8.5

One curve of an n-channel MOSFET is characterized by the following parameters: $I_D(\text{sat}) = 2 \times 10^{-4}$ A, $V_{DS}(\text{ sat }) = 4$ V, and $V_T = 0.8$ V
(a) What is the gate voltage?
(b) What is the value of the conduction parameter?
(c) If $V_G = 2$ V and $V_{DS} = 2$ V, determine I_D.
(d) If $V_G = 3$ V and $V_{DS} = 1$ V, determine I_D.
(e) For each of the conditions given in (c) and (d), sketch the inversion charge density and depletion region through the channel.

Answer:
(a)

$$V_{DS}(sat) = V_{GS} - V_T$$

or

$$4 = V_{GS} - 0.8 \Rightarrow V_{GS} = 4.8 \text{ V}$$

(b)

$$
\begin{aligned}
& I_D(\text{ sat }) = K_n\left(V_{GS}-V_T\right)^2 = K_n V_{DS}^2(\text{ sat }) \\
& \text{so} \\
& 2 \times 10^{-4} = K_n(4)^2 \\
& \text{which yields} \\
& K_n = 12.5 \mu\mathrm{A}/\mathrm{V}^2 \\
& \text{(c) } V_{DS}(\text{ sat }) = V_{GS}-V_T = 2-0.8 = 1.2 \mathrm{~V} \\
& \text{so } V_{DS} > V_{DS}(\mathrm{sat}) \\
& I_D(\mathrm{sat}) = \left(1.25 \times 10^{-5}\right)(2-0.8)^2 \\
& \text{or} \\
& I_D(\text{ sat }) = 18 \mu\mathrm{A} \\
& \text{(d)} \\
& V_{DS} < V_{DS}(\text{ sat }) \\
& I_D = K_n\left[2\left(V_{GS}-V_T\right) V_{DS}-V_{DS}^2\right] \\
& \quad = \left(1.25 \times 10^{-5}\right)\left[2(3-0.8)(1)-(1)^2\right] \\
& \text{or} \quad I_D = 42.5 \mu\mathrm{A}
\end{aligned}
$$

(e)

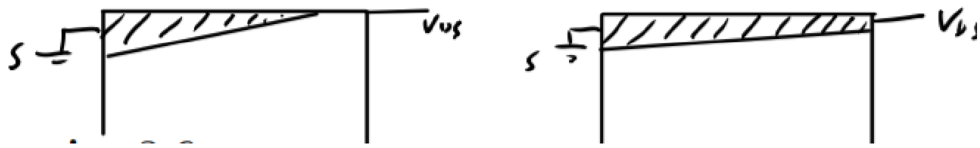


Figure 4: Figure for Problem 8.5

Exercise 8.6

An NMOS device has the following parameters: n$^+$poly gate, $t_{\text{ox}} = 400 \AA, N_a = 10^{15} \mathrm{~cm}^{-3}$, and $Q_{ss}' = 5 \times 10^{10} \mathrm{~cm}^{-2}$.

(a) Determine V_T.

(b) Is it possible to apply a V_{SB} voltage such that $V_T = 0$? If so, what is the value of V_{SB} ?

Answer:

(a) n^+poly-to-p-type $\Rightarrow \phi_{ms} = -1.0 \mathrm{~V}$

$$
\phi_{fp} = (0.0259) \ln \left(\frac{10^{15}}{1.5 \times 10^{10}}\right) = 0.288 \mathrm{~V}
$$

also

$$
\begin{aligned}
x_{dT} & = \left[\frac{4 \in_s \phi_{fp}}{e N_a}\right]^{1/2} \\
& = \left[\frac{4(11.7)\left(8.85 \times 10^{-14}\right)(0.288)}{\left(1.6 \times 10^{-19}\right)\left(10^{15}\right)}\right]^{1/2}
\end{aligned}
$$

or

$$x_{dT} = 0.863 \times 10^{-4} \text{ cm}$$

Now

$$|Q'_{SD}(\max)| = \left(1.6 \times 10^{-19}\right)\left(10^{15}\right)\left(0.863 \times 10^{-4}\right)$$

or

$$|Q'_{SD}(\max)| = 1.38 \times 10^{-8} \mathrm{C/cm}^2$$

Also

$$C_{ox} = \frac{\in_{\alpha x}}{t_{ox}} = \frac{(3.9)\left(8.85 \times 10^{-14}\right)}{400 \times 10^{-8}}$$

or

$$C_{ox} = 8.63 \times 10^{-8} \text{ F/cm}^2$$

We find

$$Q'_{ss} = \left(1.6 \times 10^{-19}\right)\left(5 \times 10^{10}\right) = 8 \times 10^{-9} \mathrm{C/cm}^2$$

Then $V_T = \frac{\left|Q'_{SD}(\max)\right| - Q'_{ss}}{C_{ox}} + \phi_{ms} + 2\phi_{fp} = \left(\frac{1.38 \times 10^{-8} - 8 \times 10^{-9}}{8.63 \times 10^{-8}}\right) - 1.0 + 2(0.288)$ or $V_T = -0.357$ V

(b) For NMOS, apply V_{SB} and V_T shifts in a positive direction, so for $V_T = 0$, we want $\Delta V_T = +0.357$ V.

So

$$\Delta V_T = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}}\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]$$

or

$$+0.357 = \frac{\sqrt{2\left(1.6 \times 10^{-19}\right)(11.7)\left(8.85 \times 10^{-14}\right)\left(10^{15}\right)}}{8.63 \times 10^{-8}} \times \left[\sqrt{2(0.288) + V_{SB}} - \sqrt{2(0.288)}\right]$$

or

$$0.357 = 0.211\left[\sqrt{0.576 + V_{SB}} - \sqrt{0.576}\right]$$

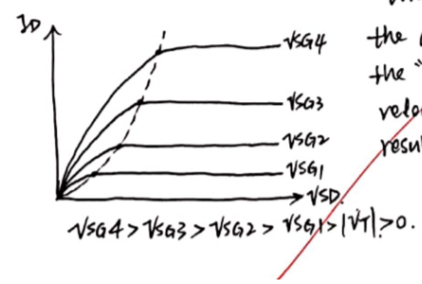
which yields

$$V_{SB} = 5.43 \text{ V}$$

Exercise 8.7

Draw the $I_{\mathrm{D}} - V_{\mathrm{SD}}$ relationship for a p-type MOSFET at different gate voltages, assuming the source is grounded. Explain why there is the saturation region, and how the saturation point changes with different gate voltages.

Answer:



When $V_{SD} > V_{SG} - |V_T|$, any increase in V_{DS} will reduce the amount of inversion charge due to the increase of the "pinch-off" region, but will also increase the charge velocity. The two effects balance each other and results in saturation.

Since $V_{SD}(sat) = V_{SG} - |V_T|$, the saturation point will increase as V_{SG} increases.

Figure 5: Figure for Problem 8.7

Reference

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