VE320 – Summer 2024

Introduction to Semiconductor Devices

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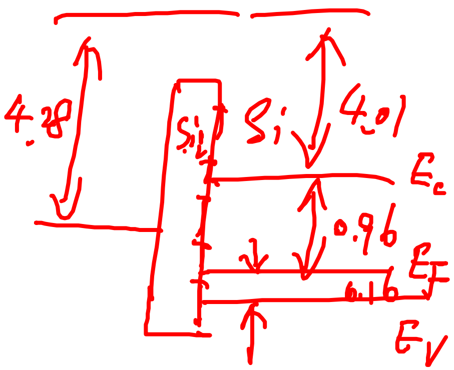
Chapter 11 Metal-Oxide-Semiconductor Field Effect Transistors: More Concepts

Problem 1

$$\phi_{ms} = \frac{W_m - W_s}{e} = \frac{4.28 - 4.97\ eV}{e} = -0.69V \qquad 1.12 - 0.16 = 0.96$$

Consider an aluminum gate–silicon dioxide–p-type silicon MOS structure with $t_{ox} = 450$ Å. The silicon doping is $N_a = 2 \times 10^{16}$ cm^{-3} and the flat-band voltage is $V_{FB} = -1.0$ V. Determine the fixed oxide charge Q'_{ss}.

$$V_T = 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \underbrace{\overset{-0.69V}{\phi_{ms}} - \frac{Q_{ss}}{C_{ox}}}_{V_{FB}}$$



$$\frac{\varepsilon_{ox}}{t_{ox}} \qquad \phi_{ms} = \frac{W_m - W_s}{e}$$

$W_s = 4.01 + 0.96$ Al: $W_m = 4.28eV$

$= 4.97eV$ Si: $\chi = 4.01eV$

$$p_0 = N_a = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$E_F - E_v = kT \ln\frac{N_v}{p_0} = 0.0259 \times \ln\frac{1.04 \times 10^{19}}{2 \times 10^{16}} = 0.16eV$$

$$V_{FB} = -1V = \phi_{ms} - \frac{Q_{ss}}{C_{ox}} = \underline{-0.69} - \frac{Q_{ss}}{C_{ox}}$$

$$-0.31 = -\frac{Q_{ss}}{C_{ox}}$$

$$= 0.31 \times 7.76\times10^{-8}\ C/cm^2$$

$$= 2.38\times10^{-8}\ C/cm^2$$

$$\frac{Q_{ss}}{C_{ox}} = 0.31 \Rightarrow Q_{ss} = 0.31 \times C_{ox}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9\times8.85\times10^{-14}}{450\times10^{-8}} = 7.67\times10^{-8}\ F/cm^2$$

Problem 2

$V_T = 0.74 + 0.3 - 0.69 - 0.05 = 0.3\,V$

Consider a MOS device with a p-type silicon substrate with $N_a = 2 \times 10^{16}\ \text{cm}^{-3}$. The oxide thickness is $t_{ox} = 15$ nm $= 150$ Å and the equivalent oxide charge is $Q'_{ss} = 7 \times 10^{10}\ \text{cm}^{-2}$. Calculate the threshold voltage for (*a*) an n$^+$ polysilicon gate, (*b*) a p$^+$ polysilicon gate, and (*c*) an aluminum gate.

-0.05

2×10^{10}

$$V_T = \underbrace{2\phi_{fp}}_{2\times0.37} + \underbrace{\frac{|Q_{SD}|}{C_{ox}}}_{0.3} + \underbrace{\phi_{ms}}_{-0.69} - \frac{Q_{ss}\cdot q}{C_{ox}}$$

(c) $\phi_{ms} = -0.69\,V$

$$\phi_{fp} = E_i - E_F = kT \ln\frac{p_0}{n_i} = 0.37\,V$$

$$0.0259 \times \ln\frac{2\times10^{16}}{1.5\times10^{10}}$$

$$p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

$$|Q_{SD}| = W_{dep}^{max} \cdot N_a \cdot q = q\,x_{TD} \cdot N_a$$

$$x_{TD} = \sqrt{\frac{2\varepsilon_{si}(2\phi_{fp})}{q N_a}}$$

$$|Q_{SD}| = \sqrt{4 q \cdot \varepsilon_{si} \cdot \phi_{fp}}$$

$$\frac{|Q_{SD}|}{C_{ox}} = \frac{t_{ox}}{\varepsilon_{ox}}\sqrt{2 q N_a \cdot \phi_{fp}}$$

$$= \frac{15\times10^{-7}}{3.9\times8.85\times10^{-14}} \times \sqrt{2\times1.6\times10^{-19} \times 2\times10^{16} \ldots}$$

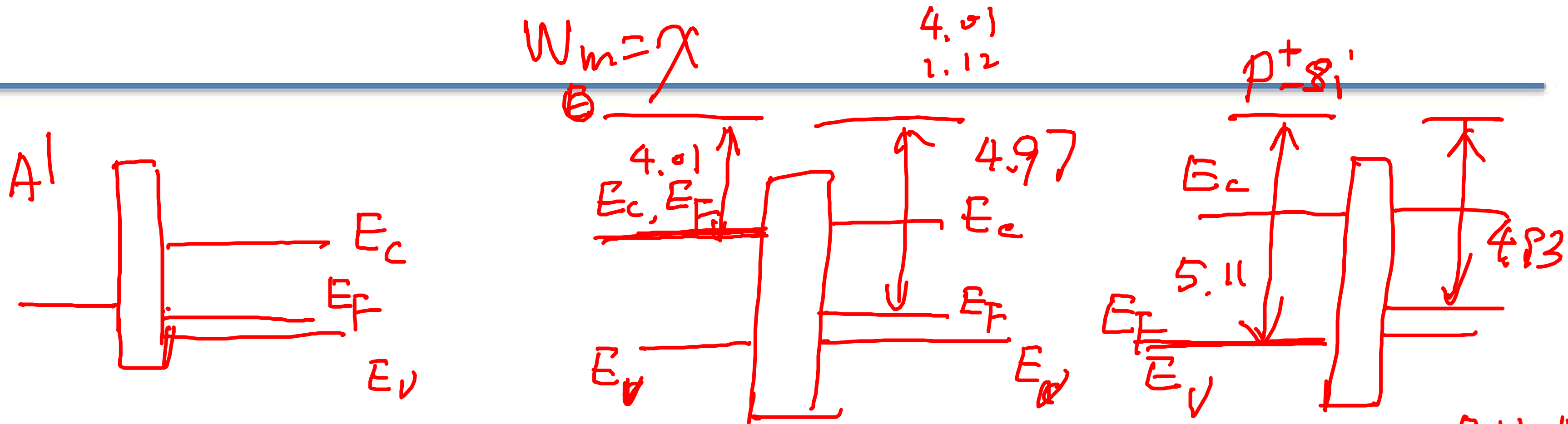
$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$\frac{|Q_{SD}|}{C_{ox}} = \frac{t_{ox}}{\varepsilon_{ox}} \sqrt{4 q N_a \cdot \phi_{fp} \varepsilon_{si}}$$

$$= \frac{15\times10^{-7}}{3.9\times8.85\times10^{-14}} \times \sqrt{4\times1.6\times10^{-19}\times2\times10^{16}\times0.37\times11.7\times8.85\times10^{-14}}$$

$$= \cancel{3.0\times10^{5}} \quad 0.3\,V$$

$$\frac{Q_{SS}}{C_{ox}} = \frac{2\times10^{10} q}{\varepsilon_{ox}/t_{ox}} = \frac{2\times10^{10}\times1.6\times10^{-19}}{3.9\times8.85\times10^{-14}/15\times10^{-7}} = 0.05\,V$$



$$\phi_{ms} = \frac{5.11-4.83}{} = 0.18$$

$-0.69V$

$$W_m = 4.01\,eV$$

$$W_s = 4.97\,eV$$

$$\phi_{ms} = \frac{W_m - W_s}{q} = -0.96\,V$$

Al: $V_T = 0.3V$

n^+-Si: $V_T = 0.3 + 0.69 - 0.96$

$= 0.3 - 0.27 = 0.03V$

p^+-Si: $V_T = 0.3 + 0.69 + 0.18$

$0.87 = 1.17V$

Problem 3

The substrate doping and body-effect coefficient of an n-channel MOSFET are $N_a = 10^{16}\ \mathrm{cm}^{-3}$ and $\gamma = 0.12\ \mathrm{V}^{1/2}$, respectively. The threshold voltage is found to be $V_T = 0.5$ V when biased at $V_{SB} = 2.5$ V. What is the threshold voltage at $V_{SB} = 0$? V_{T0}

$$V_T = V_{T0} + \gamma\left(\sqrt{|-2\phi_{fp} + V_{SB}|} - \sqrt{|-2\phi_{fp}|}\right)$$

$$0.5 = V_{T0} + 0.12 \times \left(\sqrt{|-0.35\times 2 + 2.5|} - \sqrt{0.7}\right)$$

$$= V_{T0} + 0.12\left(\sqrt{1.8} - \sqrt{0.7}\right)$$

$$= V_{T0} + 0.12 \times 0.5$$

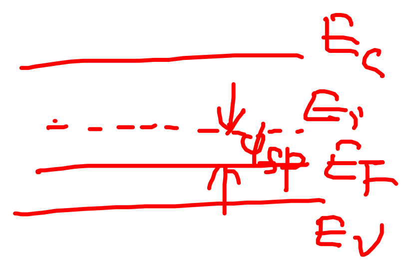
$$= V_{T0} + 0.06$$

$$V_{T0} = 0.44\ \mathrm{V}$$

$$p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

$$E_i - E_F = kT \ln \frac{p_0}{n_i}$$

$$= 0.0259 \times \ln \frac{10^{16}}{1.5\times 10^{10}} = 0.35\ \mathrm{eV}$$



$$\phi_{fp} = 0.35\ \mathrm{V}$$

$$\phi_{fp} = \frac{kT}{q} \ln \frac{N_a}{n_i} = 0.347\,V$$

$$\Delta V_T = V_T - V_{T0} = \gamma\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]$$

$$0.5 - V_{T0} = 0.12 \times \left[\sqrt{0.347 \times 2 + 2.5} - \sqrt{0.347 \times 2}\right]$$

$$V_{T0} = 0.386\,V$$

Problem 4

$I_D = k' \frac{W}{L} \left(V_{GT} * V_{min} - \frac{V_{min}^2}{2} \right) \boxed{\cancel{(1+\lambda V_{DS})}}$

Given the data in Table 1 for a short channel transistor with $V_{DSAT} = 1V$

velocity saturation

$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1+\lambda V_{DS})$

$V_{GS} - V_T > V_{Dsat}$

	V_{GS}	V_{DS}	V_{SB}	I_D (μA)	Region
1	2.5	2.5	0	84.375	velocity saturation
2	-1	-1	0	0.0	cut-off
3	0.7	0.8	0	1.04	pinch-off saturation
4	2.0	2.5	0	56.25	velocity saturation

$V_T \approx 0.6$

$V_{GS} - V_T \geq V_{Dsat}$

$V_{DSAT} = 1V$

$V_{DS} > V_{GS} - V_T$

$V_{GS} - V_T > V_{DS}$

$I_D = \mu_n C_{ox} \frac{W}{2} \left(V_{GT} \cdot V_{Dsat} - \frac{1}{2} V_{Dsat}^2 \right)$

1) Is this a NMOS or PMOS?

2) Identify the working region as one of the following four: cutoff, linear, "pinch-off" saturation or velocity saturation.

3) Calculate i) V_{T0}, ii) λ

$K' = \mu_n C_{ox} \qquad V_{GT} = V_{GS} - V_T$

velocity saturation $\quad I_D = K' \cdot \frac{W}{L} \left(V_{GT} \cdot V_{Dsat} - \frac{1}{2} V_{Dsat}^2 \right)$

linear region $\quad I_D = \mu_n C_{ox} \frac{W}{L} \left(V_{GT} - \frac{1}{2} V_{DS} \right) V_{DS}$

pinch-off saturation $\quad I_D = \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$

① $I_D = \mu_n C_{ox} \frac{W}{L} \left(V_{GT} V_{Dsat} - \frac{1}{2} V_{Dsat}^2 \right)$

$84.375\mu A = \underbrace{\mu_n C_{ox} \frac{W}{L}} \left[(2.5 - V_T) \times 1 - \frac{1}{2} \times 1^2 \right] \Rightarrow 84.375 \times 10^{-6} = k_n (2.5 - V_T - 0.5)$

$= k_n (2 - V_T)$

$\cancel{k_n = 84.375 \times 10^{-6}}$

②

③ $I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$

$1.04\mu A = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (0.7 - V_T)^2 (1 + \lambda \cdot 0.8) \Rightarrow 1.04 \times 10^{-6} = \frac{1}{2} k_n (0.7 - V_T)^2 (1 + \lambda 0.8)$

λ

④ $56.25\mu A = \underbrace{\mu_n C_{ox} \frac{W}{L}}_{k_n} \left[(2.0 - V_T) \times 1 - \frac{1}{2} \times 1^2 \right] \Rightarrow 56.25 \times 10^{-6} = k_n (1.5 - V_T)$

$k_n = 56.25 \times 10^{-6}\ A/V^2$

$V_T = 0.5V \quad \Rightarrow \frac{84.375}{56.25} = \frac{2 - V_T}{1.5 - V_T}$

1.5