HW #7 SOLUTIONS

#1 Qualitative

→ $\bar{\mu}_n$ stays constant (approximately) because the implant does not extend to the surface of the device

→ V_{FB} stays approximately constant, again because only the surface doping is important at fb.

→ W_{max} decreases because as the depletion edge extends into the silicon, it runs into the higher concentration. Then more ions are available to take up the field and W_{max} tends to clamp at the implant depth.

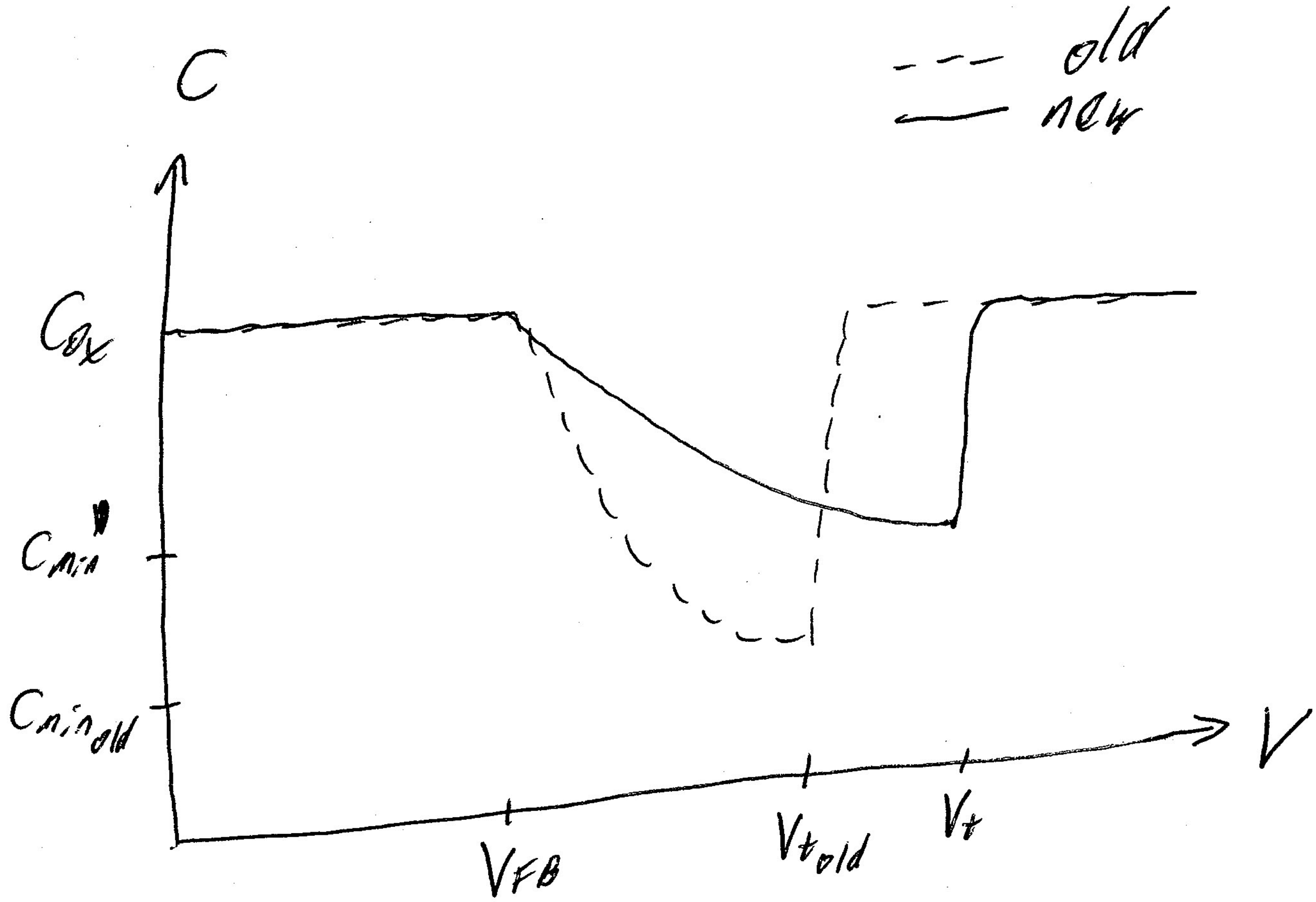
→ $V_t = \Delta\phi_{ms} + 2\phi_f + \frac{t_{ox}}{\epsilon_{ox}}\sqrt{2q\epsilon_s N_a 2\phi_f}$

Since N_a at W_{max} has effectively increased, V_t increases, slightly.

Note that ϕ_s must remain $= 2\phi_f$, a constant,

$\therefore$ $E_{ox}\uparrow$ relative to the old values

$\Delta V_{ox}\uparrow$



$V_t \uparrow$

$W_{max} \downarrow$, $\therefore$ $C_{min} \uparrow$

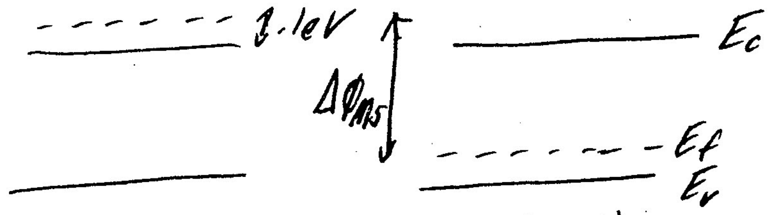
V_{FB} const

C_{ox} const

(2) <u>Quantitative</u>

a.) $V_{FB} = \Delta \phi_{ms} - \frac{Q_f}{C_f}$

$\Delta \phi_{ms}$:



$p = N_v e^{-(E_f - E_v)/kT}$

$10^{16} = 1.04 \times 10^{19} e^{-(E_f - E_v)/kT}$

$E_f - E_v = .18 eV$

$q \Delta \phi_{ms} = -(E_c - E_f + .1eV)$

$\Delta \phi_{ms} = -(.92 eV + .1eV) = -1.02 eV$

$\frac{Q_f}{C_f}$:

$Q_f = 2 \times 10^{-8}$ coul

$C_f = \frac{\epsilon_{ox}}{\frac{1}{2} T_{ox}} = 2.3 \times 10^{-7}$ F/cm^2

$\frac{Q_f}{C_f} = .09 V$

$\boxed{V_{FB} = -1.11 V}$

b) $V_t = V_{FB} + 2\phi_f + |V_{BS}| + \frac{t_{ox}}{\epsilon_{ox}}\sqrt{2q\epsilon_{Si}N_a(2\phi_f + |V_{BS}|)}$

$$2\phi_f = 2kT \ln\frac{N_a}{n_i} = .71V$$

$$|V_{BS}| = 2V$$

$$V_t = -1.11 + .71 + 2 + .82$$

$$\boxed{V_t = 2.42\ V}$$

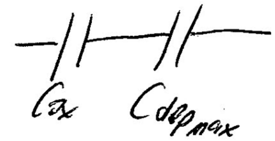
c) $I_{Dsat} = \frac{Z\bar{\mu}_n C_{ox}}{2L}(V_g - V_t)^2$

$$C_{ox} = 115\ nF/cm^2$$

$$\boxed{I_{Dsat} = .21\ mA}$$

d.) We already know V_{FB}, V_t, C_{ox},

All we need is C_{min}

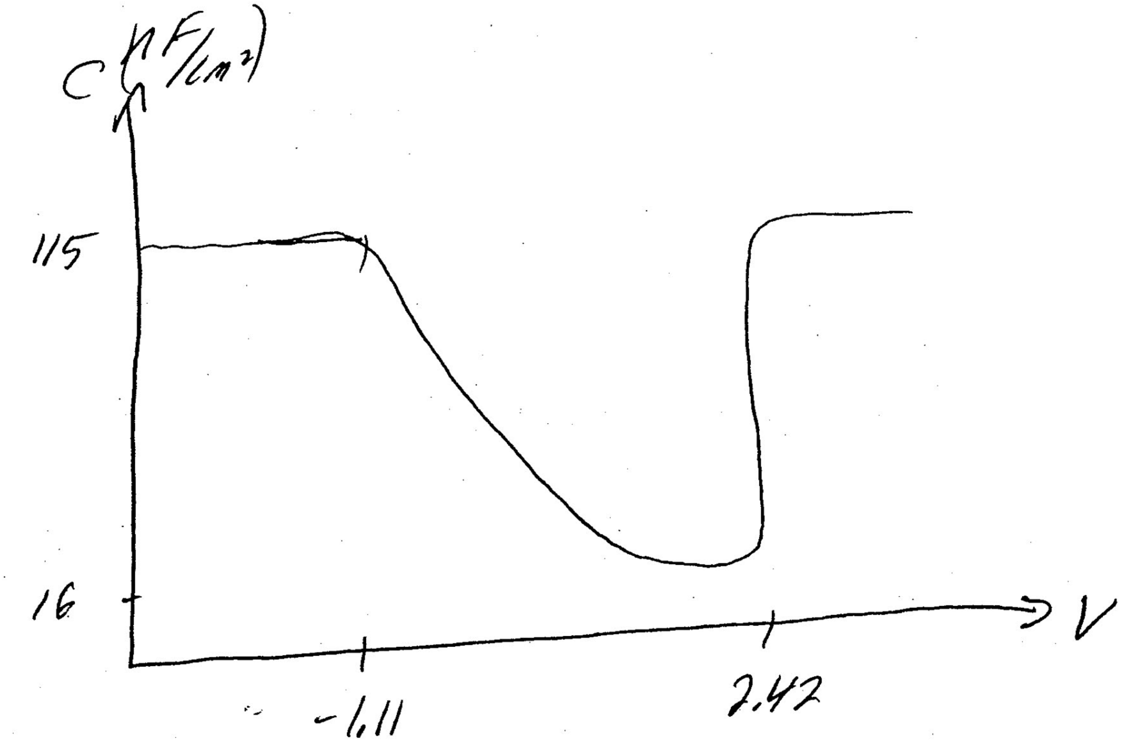
$C_{min} \rightarrow$ 

$C_{depmax} = \frac{\epsilon_s}{W_{max}}$

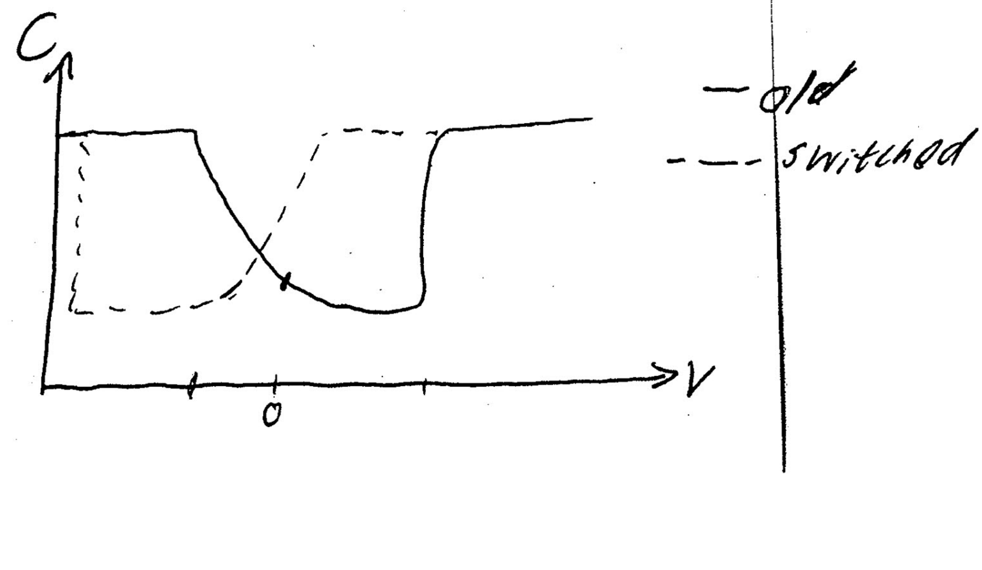
$$W_{max} = \sqrt{\frac{2\epsilon_{Si}(2\phi_f + |V_{BS}|)}{qN_a}} = .59\ \mu m$$

$$C_{depmax} = \frac{\epsilon_s}{W_{max}} = 18\ nF/cm^2$$

$$C_{min} = \frac{C_{ox} C_{dep}}{C_{ox} + C_{dep}} = 16 nF/cm^2$$

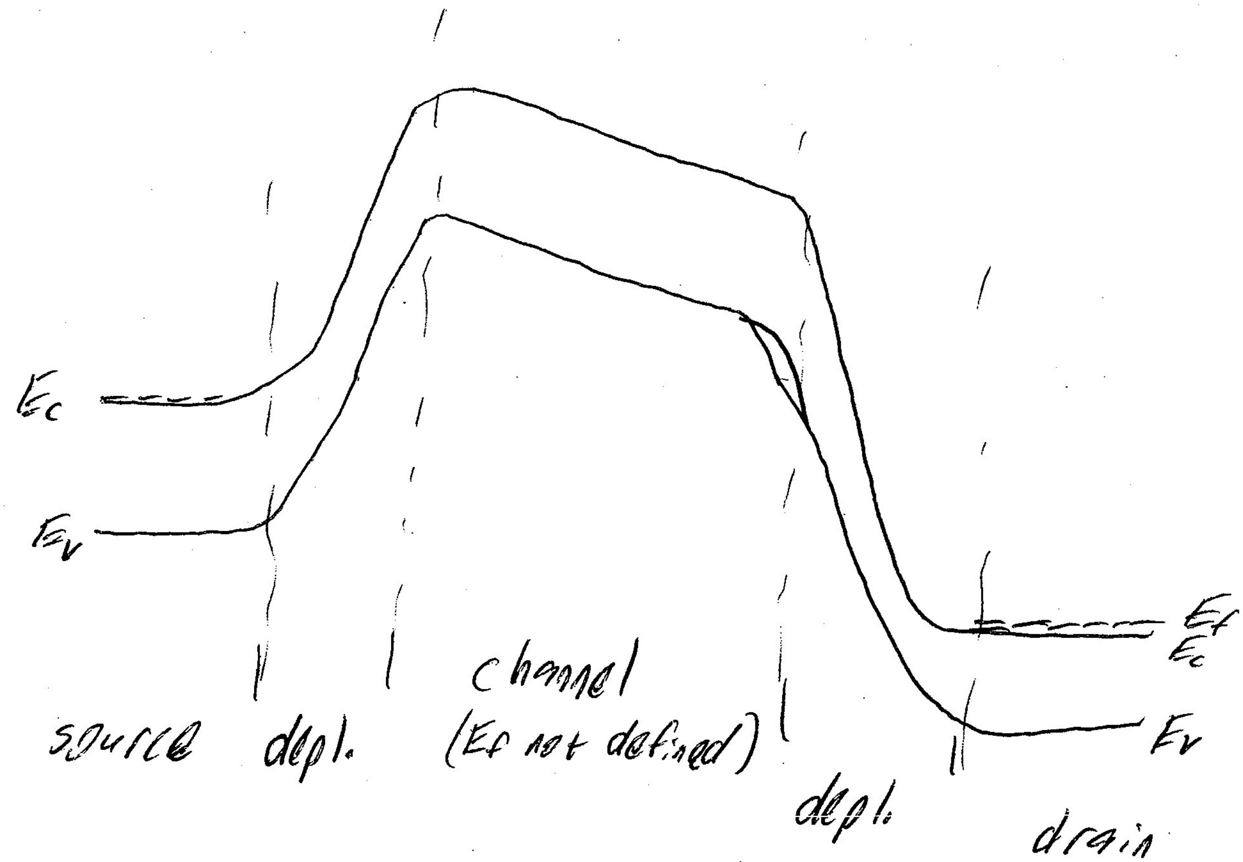


If n & p are switched, then $\Delta\phi_{ms}$, $2\phi_f$ & $\Delta\phi_{ox}$ change signs. $-\frac{Q_f}{C_f}$ stays constant. Also the voltages must change sign or we will forward bias the source-substrate & drain substrate junctions.

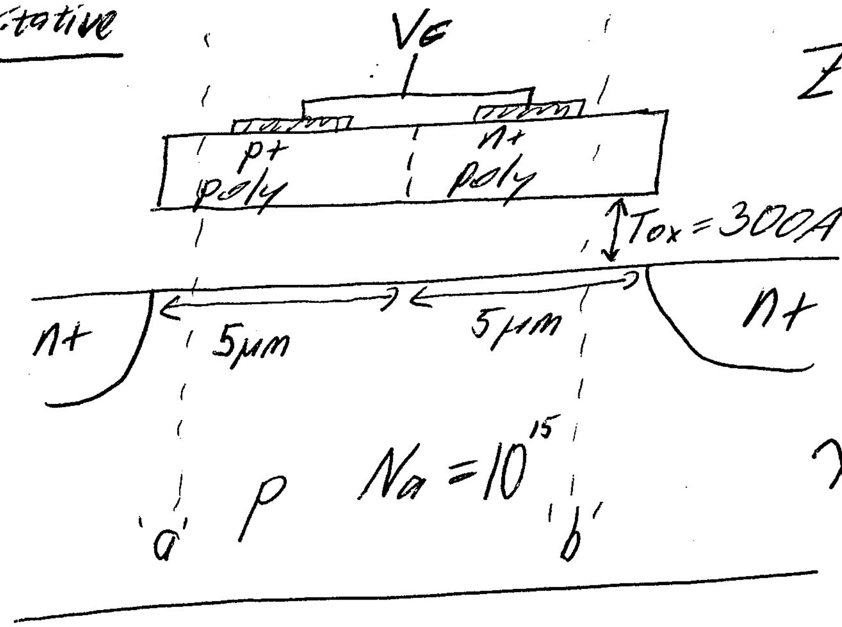


e.) If $V_g = 0V$ & $V_{sub} = 0V$, then $\phi_s = 0V$

$V_s = 2V$ $V_d > V_{dsat} (> 2V)$



③ Quantitative



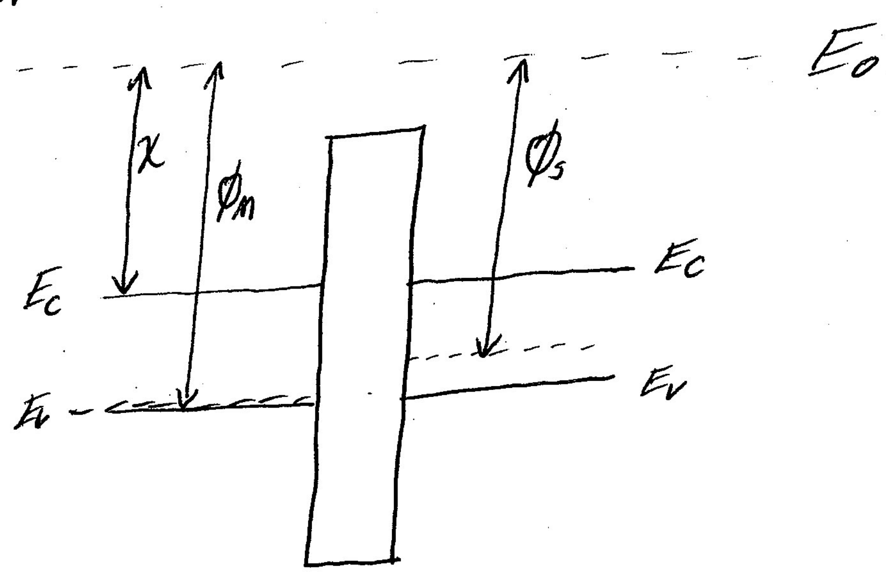
$Z = 10\,\mu m$

$\chi_{Si} = 4.05\,eV$

a.) Find $C_{ox}\left(\frac{F}{cm^2}\right)$ $\quad C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.854\times10^{-14}\frac{F}{cm})}{(300\times10^{-8}\,cm)}$

$$C_{ox} = 1.15\times10^{-7}\,\frac{F}{cm^2}$$

b.) V_{FB} @ 'a'



$$\phi_m = \chi + E_c - E_F$$
$$= \chi + E_c - E_v = \chi + E_g$$
$$= 4.05 + 1.1\,eV = \underline{5.15\,eV}$$

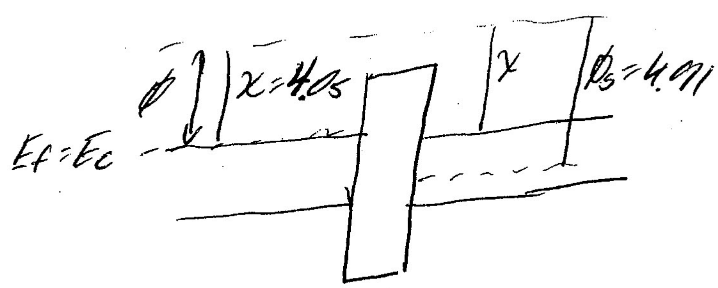
$$\phi_s = \chi + E_c - E_f$$
$$= \chi + [(E_c - E_v) - (E_f - E_v)]$$
$$= 4.05\,eV + [1.1\,eV - (E_f - E_v)]$$

$$-(E_f - E_v) = kT \ln \frac{N_a}{N_v}$$
$$= .026\,eV \ln \frac{10^{15}\ cm^{-3}}{1.04 \times 10^{19}\ cm^{-3}}$$
$$E_f - E_v = .24\,eV$$

$$\phi_s = 4.05\,eV + (1.1\,eV - .24\,eV)$$
$$\underline{\phi_s = 4.91\,eV}$$

$$\boxed{qV_{FB_a} = \phi_m - \phi_s = +.24\,eV}$$

V_{FB} @ 'b'



$\phi_m = \chi = 4.05\,eV$ since $E_c = E_f$

$\phi_s = 4.91\,eV$ as before

$$\boxed{qV_{FB_b} = \phi_m - \phi_s = -.86\,eV}$$

c.) $V_T = V_{FB} + 2\phi_f + \frac{t_{ox}}{\epsilon_{ox}} \sqrt{2q\epsilon_{si} N_a 2\phi_f}$

$$\phi_f = \frac{kT}{q} \ln \frac{N_a}{n_i}$$

$$\phi_f = .30\,V$$

$$2\phi_f = .60\,V$$

$$\frac{t_{ox}}{\epsilon_{ox}} \sqrt{2q\epsilon_{si} N_a 2\phi_f} = .12\,V$$

at point 'a':

$$V_{T_a} = V_{FB_a} + .60V + .12V$$

$$V_{T_a} = +.24V + .60V + .12V$$

$$\boxed{V_{T_a} = .96\,V}$$

at point 'b':

$$V_{T_b} = V_{FB_b} + .60V + .12V$$

$$V_{T_b} = -.86 + .60V + .12V$$

$$\boxed{V_{T_b} = -.14\,V}$$

d.) W_{max} is the same for both 'a' & 'b'

$\begin{pmatrix} or \\ W_T \end{pmatrix}$

$$W_{max} = \sqrt{\frac{2 \epsilon_{Si}}{q N_a} 2\phi_f}$$

$$\boxed{W_{max} = .88 \mu m}$$

e.) Draw a C-V curve for the structure

C_{min} = C_{ox} in series with $C_{depletion}$)

$$C_{dep} = \frac{\epsilon_s}{W} = \frac{(11.7)(8.854 \times 10^{-14} \frac{F}{cm})}{(.88 \times 10^{-4}\ cm)}$$

$$\underline{C_{dep} = 1.18 \times 10^{-8}\ F/cm^2}$$

$$\frac{1}{C_{min}} = \frac{1}{C_{dep}} + \frac{1}{C_{ox}}$$

$$C_{min} = \frac{C_{dep} C_{ox}}{C_{dep} + C_{ox}}$$

$$\boxed{C_{min} = 1.07 \times 10^{-8}\ F/cm^2}$$

$C_{ox} = 1.15 \times 10^{-7} \frac{F}{cm^2}$

$C_{min} = 1.07 \times 10^{-8} \frac{F}{cm^2}$

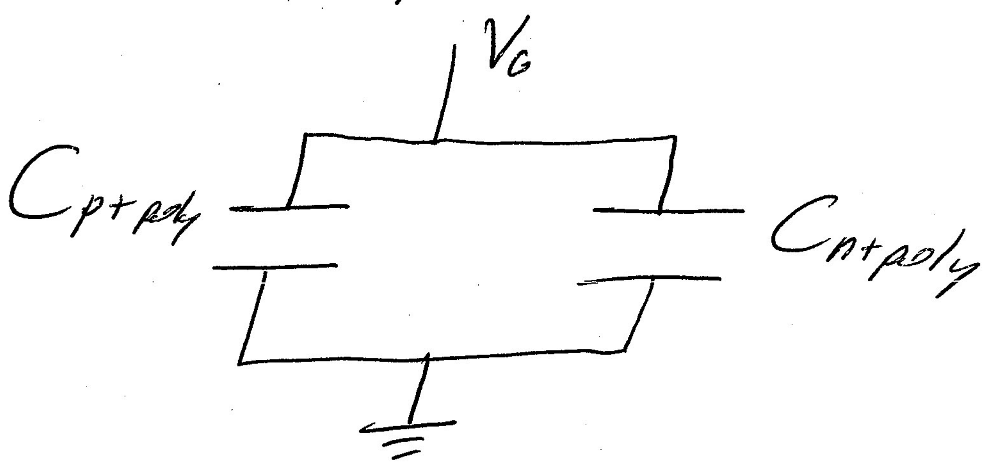
$V_{FB_a} = .24V$

$V_{T_a} = .96V$

$V_{FB_b} = -.86V$

$V_{T_b} = -.14V$

Now this device is essentially two capacitors in parallel



The area for both capacitors is

$A = (L)(Z) = (5\mu m)(10\mu m)$

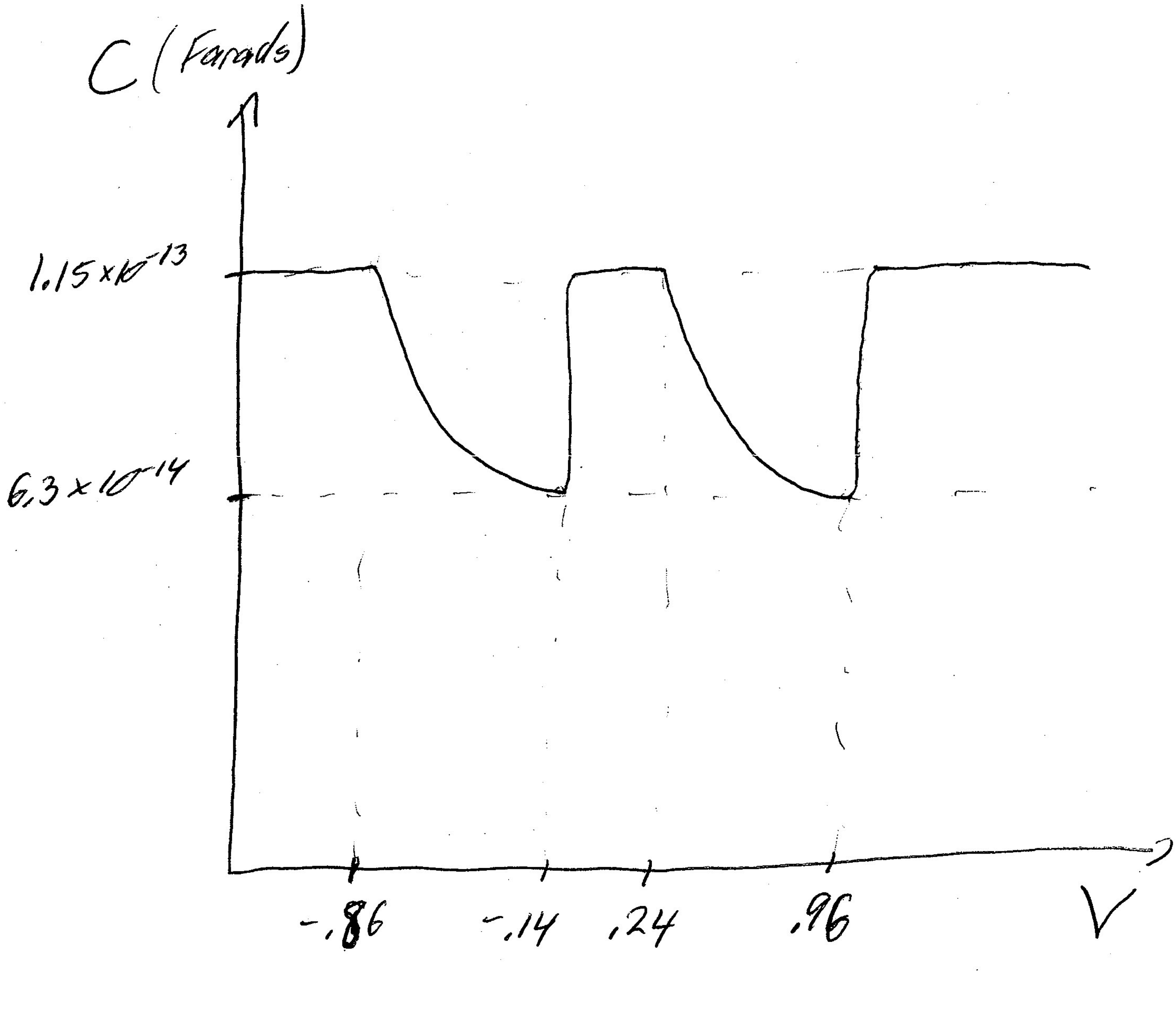
$A = 5.0 \times 10^{-7} cm^2$

$(C_{ox})(A) = 5.75 \times 10^{-14}$ F

$(C_{min})(A) = 5.35 \times 10^{-15}$ F

$2 C_{ox} A = 1.15 \times 10^{-13}$ F

$C_{min} A + C_{ox} A = 6.3 \times 10^{-14}$ F



[*Problem #1, final exam, spring 2007*]

4. a) Yes, but only a little. The substrate is highly doped and the gate oxide is very thin. Both of these mitigate short channel effects. So one would likely see velocity saturation and channel length modulation, but only a little V_T lowering and no punch-through at standard V_d.

b) $V_T = V_{FB} + 2\phi_f + \frac{\epsilon_{ox}}{t_{ox}}\sqrt{2q\epsilon_{si} N_a 2\phi_f} + \Delta V_T(V_T \text{ lowering})$

$$\Delta V_T = -\frac{q N_a W_T}{C_{ox}} \frac{r_j}{L}\left(\sqrt{1+\frac{2W_T}{r_j}} - 1\right)$$

$$q\phi_f = E_f - E_i = kT \ln \frac{N_a}{n_i} \approx .42V \qquad 2\phi_f \approx .83V$$

$$W_T = \sqrt{\frac{2\epsilon}{qN_a} 2\phi_f} \sim .1\mu m$$

$$r_j = .2\,\mu m \qquad L = .5\,\mu m$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = 8.63 \times 10^{-7}\ F/cm^2$$

$$\underline{\Delta V_T \approx -.03V}$$

$$V_{FB} = -\left[(E_f - E_c)_{poly} + (E_c - E_f)_{substrate}\right]$$

$$= -\left[.2eV + .55eV + .42eV\right]$$

$$\cancel{1}(E_c - E_i) + (E_i - E_f)$$

$$V_{FB} = -1.17\,V$$

$$\frac{t_{ox}}{\epsilon_{ox}}\sqrt{2q\epsilon_{Si} N_a 2\phi_f} = .19\,V$$

$$V_T = -1.17 + .83 + .19 - .03$$

$\boxed{V_T = -.18V}$ This is <u>a depletion mode device</u>. The oxide is too thin for the channel length.

It is "on" even when $V_g = 0V$.

c.) Saturation:

$$I_d = \frac{Z\mu C_{ox}}{2L}(V_g - V_t)^2$$

$$\mu_A(N_a = 10^{17}) \approx 801 \frac{cm^2}{V\text{-}s}$$

w/ interface scattering μ_n will be <u>lower</u>

I'll use $\bar{\mu}_n \approx 400 \frac{cm^2}{V-s}$ but any reasonably lower number is fine

$$I_d = \frac{(\cancel{.5\mu m})(400\frac{cm^2}{V-s})(8.63\times10^{-7}\frac{F}{cm^2})}{2(\cancel{.5\mu m})}(1-.18V)^2$$

$$\boxed{I_d = .24 mA}$$

d.) The HfO_2 will have the bigger effect on V_T because ϵ_{ox} is explicitly in the term $\frac{\epsilon_{ox}}{t_{ox}}\sqrt{2q\epsilon_{si}N_a 2\phi_f}$.
The strained silicon has a higher mobility but this does not directly affect V_T & the strain impact on ϵ_{si}, E_g, n_i etc... is relatively small.

e.) C-V Transistor 1: $V_T = -.18V$

$V_{FB} = -1.17V$

$C_{ox} = 8.63\times10^{-7}\ F/cm^2$

$$C_{min} = C_{HF} = \frac{C_{ox}}{1+\frac{\epsilon_{ox}W_T}{\epsilon_{si}t_{ox}}}$$

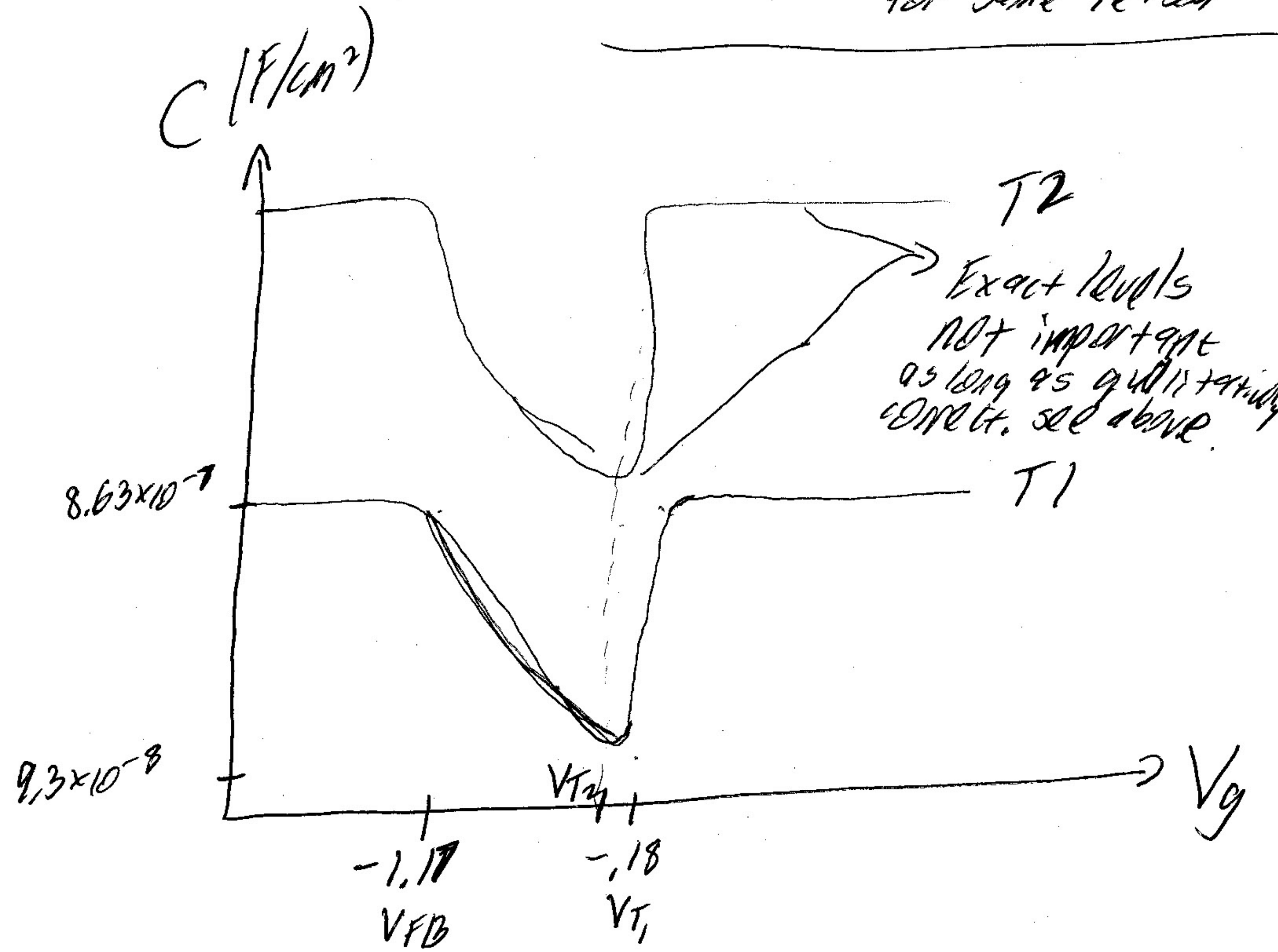
$$C_{min} \approx \frac{C_{ox}}{9.3} \approx 9.3\times10^{-8}\frac{F}{cm^2}$$

Transistor 2: V_{FB} same as Trans. #1

V_T will be slightly lower because $\epsilon_{HfO_2} > \epsilon_{SiO_2}$

C_{ox} will be much higher (ϵ_{HfO_2})

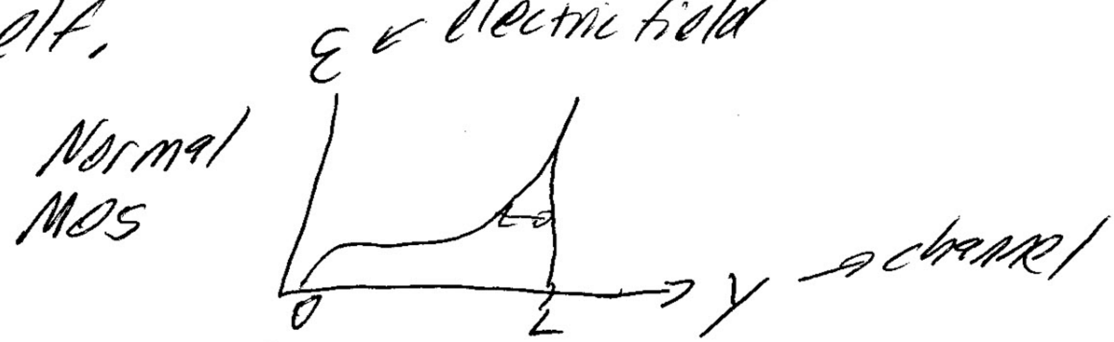
C_{min} will be higher for same reason

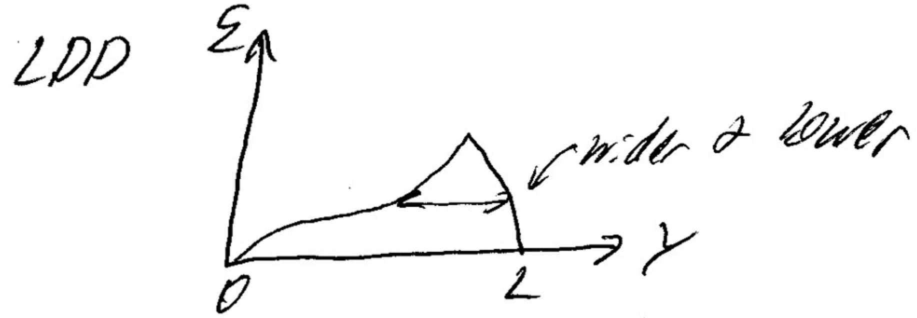


[*Problem #3, final exam, spring 2007*]

5. LDD

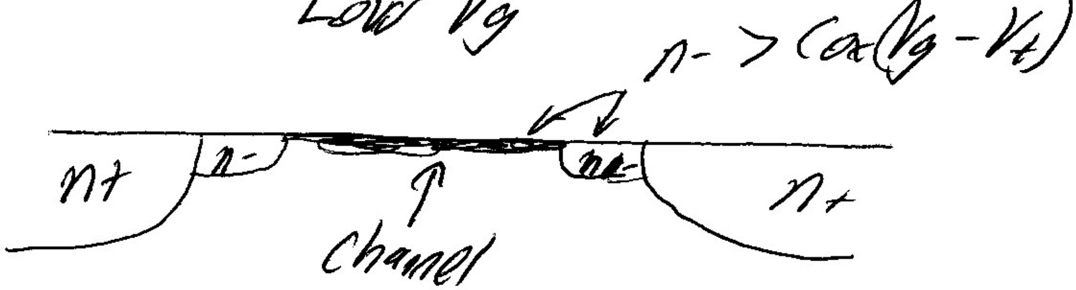
a.) LDD reduces hot carriers because the "pinch off" region is extended by the n- region. The light doping acts as a resistor & drops some of the voltage across itself.





b.) The charge in the channel is $\sim C_{ox}(V_g - V_t)$. As V_g increases, the charge density increases and begins to exceed the level of n- in the lightly doped regions.

Low V_g



High V_g