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Homework Assignment # 11 Solutions

Note :

$|f_F|$ is sometimes labeled as $|f_p|$ or $|f_n|$ in equations (representing the value of $|f_F|$ for p-type and n-type substrates respectively)

Problem 1

(a) NMOS

$|\phi_F| = 0.026 \ln\frac{2\times10^{16}}{1.45\times10^{10}} = 0.37$ V

$\mathbf{V_{FB}} = \phi_{MS} = 4.15 - (4.15+0.56+0.37) = \mathbf{-0.93V}$

$\mathbf{V_{Si}}$ at onset of strong inversion = 2 $|\phi_F|$ = **+0.74V**

$x_{dmax} = (\frac{2\varepsilon_s \bullet 2|\phi_F|}{qN_a})^{1/2} = 0.22\ \mu m$

$Q_{dmax} = N_a \bullet x_{dmax} = 4.4\times10^{11}\ q/cm^2$

$x_{ox} = 4.5\times10^{-6}$cm implies $C_{ox} = 7.7\times10^{-8}\ F/cm^2$

$\mathbf{V_{ox}} = \frac{Q_{dmax}}{C_{ox}} = \mathbf{+0.91V}$

$\therefore\ \mathbf{V_{TN}} = V_{FB} + V_{si} + V_{ox} = -0.93 + 0.74 + 0.91 = \mathbf{+0.72V}$

(b) PMOS

$\mathbf{V_{FB}} = 4.15 - (4.15+0.56 - 0.37) = \mathbf{-0.19V}$

$\mathbf{V_{Si}}$ at onset of strong inversion = -2 $|\phi_F|$ = **-0.74V** (minus because of opposite charge of depletion region)

$\mathbf{V_{ox}} = \mathbf{-}\frac{Q_{dmax}}{C_{ox}} = \mathbf{-0.91V}$ (minus because of opposite charge of depletion region)

$\therefore\ \mathbf{V_{TP}} = V_{FB} + V_{si} + V_{ox} = -0.19 - 0.74 - 0.91 = \mathbf{-1.84V}$

Problem 2

a.) $|\phi_p| = 0.026 \ln\frac{5\times10^{15}}{1.45\times10^{10}} = 0.332$ volts $\therefore\ \phi_{MS} = -0.56 - |\phi_p| = -0.892$ volts

$\therefore\ V_T = \phi_{MS} - \frac{Q_f}{C_{ox}} + 2|\phi_p| + \frac{\sqrt{4\varepsilon_s qN_a|\phi_p|}}{C_{ox}}$

$\Rightarrow 1.0 = -0.892 + 0.664 + \frac{1}{C_{ox}}[-1.6\times10^{-19}\times3\times10^{10} + (4\times1.04\times10^{-12}\times1.6\times10^{-19}\times5\times10^{15}\times0.332)^{1/2}]$

$\Rightarrow C_{ox} = 2.33\times10^{-8}\ F/cm^2$ $\quad\therefore\ \mathbf{x_{ox}} = \frac{\varepsilon_{ox}}{C_{ox}} = \frac{3.45\times10^{-13}\ F/cm^2}{2.33\times10^{-8}\ F/cm^2} = 1480$ Å=**148 nm**

b.) Phosphorus (donor dopant) implant will give a negative V_T shift.

$\Delta V_T = 1 - (-2) = 3$ volts (shifted from +1 volt to - 2 volts)

$\therefore\ \Delta V_T = \frac{q\phi}{C_{ox}}$ by assuming all implanted phosphorus in Si are inside Si and localized at Si-SiO_2 interface.

$\therefore$ **Implant dose** $f = \frac{\Delta V_T \bullet C_{ox}}{q} = \frac{3\times2.33\times10^{-8}}{1.6\times10^{-19}} = \mathbf{4.4´\ 10^{11}/cm^2}$

Problem 3

C_{ox}=1.57 ×10 $^{-7}$ F /cm^2

With Na=2*10^{16}/cm3 and Nd=10^{16}/cm3

ϕn=0.35V

ϕp=0.37V

V_{TN}=(4.15-4.15-0.56-0.37)+2*0.37+0.45= **+0.26V**

V_{TP}=(4.15-4.15-0.56+0.35)-2*0.35-0.3= **-1.21V**

Goal is to make V_{TN} (new) = -V_{TP} (new) after threshold implant

The same implant will give identical V_T shift for both NMOS and PMOS.

Therefore $V_{TN} + \Delta V_T = -(V_{TP}+\Delta V_T)$

We will find out later what specie is required from the algebraic sign of ΔV_T.

ΔV_T=(1.21-0.26)/2 = +0.475V

(**+ shift means p-dopant implant such as Boron**)

$$\textbf{Boron dose} = \frac{0.475 \times 1.57 \times 10^{-7}}{1.6 \times 10^{-19}} = \mathbf{4.66 \times 10^{11}\ /cm^2}$$

Problem 4

$I_D = \mu_n C_{ox} W/L\,(V_G - V_T)V_{DS}$ for **small** V_{DS}

(a) From the intercepts on the x-axis, V_T (V_B =0) =1 .5V, **V_T (V_B=-2V) = 3.5V**

(b) $\Delta V_T = \gamma\ [\ (2|\phi_p| + V_{SB})^{1/2} - (2|\phi_p|)^{1/2}\ ]$ where the body coefficient $\gamma = \dfrac{\sqrt{2\varepsilon_s q N_a}}{C_{ox}}$

Since $|\phi_p| = 0.026 \ln\left(\dfrac{N_a}{1.45 \times 10^{10}}\right)$ and with V_{SB} =2V, we can solve for N_a by iteration.

N_a~ 2 x 10^{16}/cm^3

(c) The slope of the I_D versus V_G curves is $\mu_n C_{ox}(W/L)V_{DS}$ = 10uA/V

With C_{ox} =3 .45 x 10 $^{-8}$ F/cm^2, W/L =10, V_{DS} = 50mV

μ_n ~ 580 cm2/V-sec

Note: For carrier mobility of a MOSFET channel, one cannot simply use the mobility curves due to dopant concentration. Scattering mechanisms at the oxide-Si interface usually reduces the mobility. The rule of thumb is approximating the channel mobility as ½ of the bulk mobility.

(d) We know V_T (V_B =0) =1 .5V

For V_G = 10V, $\mathbf{I_{Dsat}} = \dfrac{\mu_n C_{ox} W}{2L}(V_G - V_T)^2$ ~ **7.2 mA.**

Problem 5

(a) $\dfrac{C_{min}}{C_{ox}}$ = 0.52 from graph = $\dfrac{1}{1+\dfrac{C_{ox}x_{dmax}}{\varepsilon_s}}$ $\therefore$ $\dfrac{C_{ox}x_{dmax}}{\varepsilon_s}$ =0.923

x_{dmax} = 0.72 μm

(b) $\dfrac{q\,N_a xdmax^2}{2\varepsilon_s} = 2|\phi_p| = 2\,\dfrac{kT}{q}\ln\dfrac{N_a}{n_i}$

$$\therefore \frac{N_a}{\ln\dfrac{N_a}{1.45\times10^{10}}} = 1.3\times10^{14}$$

By iteration, $\mathbf{N_a \sim 1.5 \times 10^{15}\ /cm^3}$

(c) $V_T = -3V$, $C_{ox} = 1.33\times10^{-8}\ F/cm^2$, $|\phi_p| = 0.3V$

From $V_T = \phi_{MS} - \dfrac{Q_f}{C_{ox}} + 2|\phi_p| + \dfrac{\sqrt{4\varepsilon_s q N_a|\phi_p|}}{C_{ox}}$, $\phi_{MS} = 0.57V$

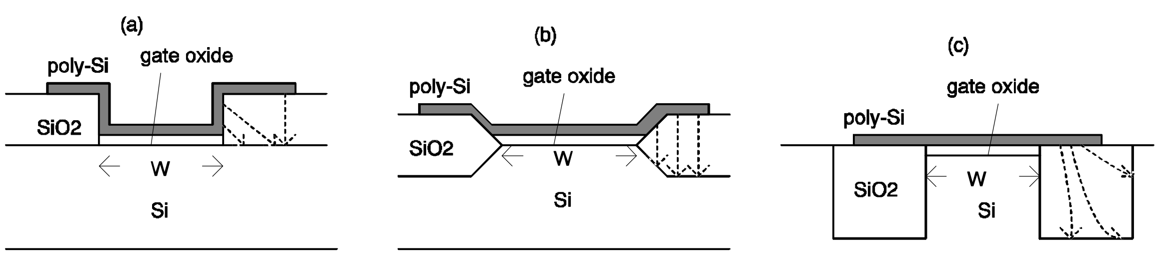
Since $\phi_s = 4.91$ V

$\therefore$ $\mathbf{q\phi_M = 4.34eV}$

Problem 6

The narrow width effect is caused by the excess depletion charge in Si which the gate has to create outside the W region (V_T will go up as compared with the ideal case). Since the LOCOS structure (b) has the most gradual rise of oxide thickness around the perimeter, the gate will have the most coupling with the substrate Si to create excess depletion charges. The oxide cut (a) has an oxide slope of 90 °, the effective coupling is less. For the oxide trench (c) , there is no extra Si substrate next to the channel to create excess depletion charge. *Structure (c) will exhibit the least narrow width effect.*

The gate coupling to the Si substrate can also be visualized by the length of the dashed E-field lines (the longer the lines, the less coupling). In terms of narrow width effect, ranking in decreasing order will be : LOCOS, oxide cut, oxide trench.



Problem 7

(a) $\mathbf{V_G\ max}$ = 8×10^6 V/cm $\times 2\times10^{-6}$ cm = **16 V**

(b) $C_{ox} = 1.725\times10^{-7}\ F/cm^2$

With $N_a = 10^{16}/cm^3$

$|\phi_F| = 0.35V$

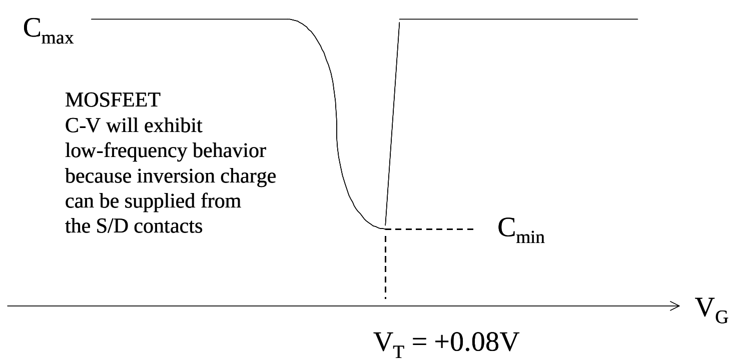
$\mathbf{V_{TN}} = -0.56 + |\phi_F| + \dfrac{\sqrt{4\varepsilon_s q N_a |\phi_F|}}{C_{ox}} = \mathbf{+0.07V}$

(c) $\mathbf{x_{dmax}} = \sqrt{\dfrac{4\varepsilon_s|\phi_F|}{qN_a}} = \mathbf{3\ ´\ 10^{-5}cm}$

(d) $V_G - V_T = 5 - 0.08 < V_D = 5V$. ***Transistor is in saturation mode***.
$\mathbf{I_{Dsat}} = k[(V_G - V_T)^2/2] = \mathbf{605}$m**A**

(e) A boron threshold implant will shift the V_T for more positive threshold voltagevalues.
D$\mathbf{V_T} = q\ \phi / C_{ox} = 1.6 \times 10^{-19} \times 10^{12} / 1.725 \times 10^{-7} =$ **0.93V**
New $\mathbf{V_T}$ = 0.93+0.07 = **1.0V**

(f) $V_G - V_T = 5 - 1.01 < V_D = 5V$. Transistor is in saturation mode.
$\mathbf{I_{Dsat}} = k[(V_G - V_T)^2/2] = \mathbf{398}$m**A**
(g)



(h) $\mathbf{C_{max}} = C_{ox} = \mathbf{1.725\ ´\ 10^{-7}\ F/cm^2}$

$\mathbf{C_{min}} = C = \dfrac{1}{1/C_{ox} + x_{dmax}/\varepsilon_s} = \mathbf{2.88´\ 10^{-8}\ F/cm^2}$