Microelectronic Devices and Circuits- EECS105

First Midterm Exam

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Your Name: Official (last) Solutions (first)

Your Signature: C. J. SPANOS

1. *Print and sign your name on this page before you start.*
2. *You are allowed a single, handwritten sheet with formulas. No books or notes!*
3. *Do everything on this exam, and make your methods as clear as possible.*

Problem 1	/35
Problem 2	/35
Problem 3	/15
Problem 4	/15
TOTAL	m 71 /100

σ 15

Problem 1 of 4 (35 points)

Answer each question briefly and clearly. Assume room temperature and thermal equilibrium unless otherwise noted.
What types and concentrations of charges exist in intrinsic silicon? (6pts)

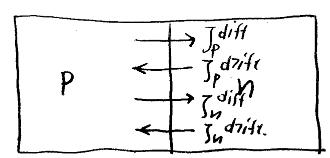
$n \simeq 10^{10}/cm^3$ (free electrons)
$p \simeq 10^{10}/cm^3$ (free holes)

List the type (holes, electrons, ions), sign (+/-) and concentrations of all charges in silicon doped with $10^{17}/cm^3$ As and $10^{15}/cm^3$ Boron. Be sure to mention whether each charge is mobile or not. (8pts)

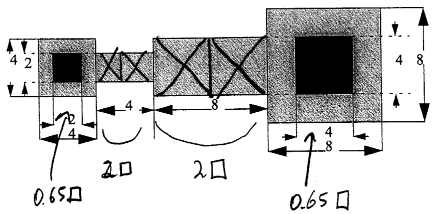
As dominates, so material is n-type
we have: $\sim 10^{17}$ electrons$/cm^3$, 10^3 holes$/cm^3$ and also:
10^{17} positive As ions$/cm^3$ and 10^{15} negative B ions$/cm^3$

What are the four types of currents you can find across a p-n junction in thermal equilibrium? (6pts)

$$J_p^{diff} + J_p^{drift} + J_n^{diff} + J_n^{drift} = 0$$



Find the contact-to-contact resistance of the following structure (drawn to scale), if the Rs is 10 Ohms/square. Assume that "dogbone" contact areas amount to 0.65 squares. (8pts)



we have a total of 5.3□ × 10Ω/□ = $\underline{53\ \Omega}$

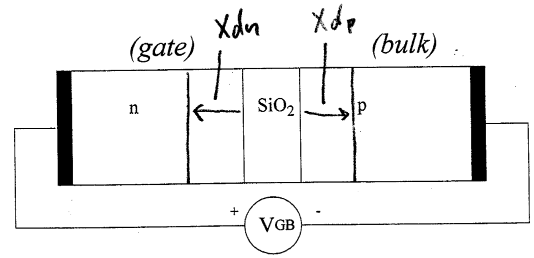
You are given doped silicon that at thermal equilibrium has an electron concentration $10^{16}/cm^3$. What is the built-in potential with reference to intrinsic silicon? What would be the concentration of electrons at some point within this lattice, if you raised the potential at that point by 120mV? (7pts)

$\varphi_n = 6 \times 60mV = 360mV$

if we raised the potential to $360mV + 120mV = 480mV$ then the concentration of electrons would be $10^{18}/cm^3$ to satisfy the 60mV rule.

Problem 2 of 4 (35 points)

Consider the following structure that consists of n-type silicon ($10^{16}/cm^3$), 0.1μm of SiO_2 and p-type silicon ($10^{16}/cm^3$). (Hint: *This is nothing more than a MOS capacitor whose gate is made out of weakly doped silicon. This means that the gate will also deplete and/or invert under proper conditions. The symmetric concentrations in the channel and the gate should make this problem easy to solve...*)



a. Calculate the depth of the depletion regions when $V_{GB} = 0$. (10pts)

in thermal equilibrium we have:

$$\varphi_n - \varphi_p = \underset{\uparrow \text{ drop across the n depletion}}{\frac{q N_d \cdot X_{dn}^2}{2\varepsilon_{si}}} + \underset{\uparrow \text{ drop across the p depletion}}{\frac{q N_a \cdot X_{dp}^2}{2\varepsilon_{si}}} + \underset{\uparrow \text{ drop across Cox.}}{\frac{q N_a X_{dn}}{C_{ox}}}$$

substitute: $\varphi_n = 0.36V$, $\varphi_p = -0.36V$, $q = 1.6 \cdot 10^{-19} Cb$, $N_d = N_a = 10^{16}/cm^3$, $X_{dp} = X_{dn}$, and $C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = 3.45 \cdot 10^{-8} F/cm$.

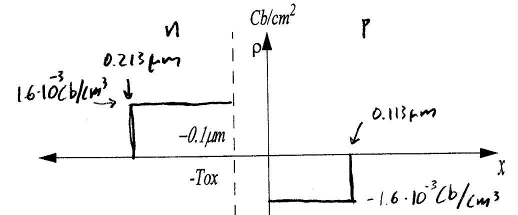
$$\Rightarrow \underbrace{\frac{q \cdot N_d}{\varepsilon_s}}_{a} X_{dn}^2 + \underbrace{\frac{q N_d}{C_{ox}}}_{b} X_{dn} \underbrace{- 0.72V}_{c} = 0 \Rightarrow X_{dn} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \underline{\underline{0.112\mu m}}$$

since system is symmetric:

$\underline{\underline{X_{dp} = 0.112\mu m}}$

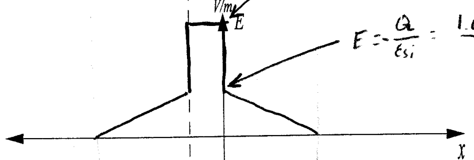
b. Draw the charge density, E-field and potential plots in thermal equilibrium (V_{GB} = 0). Mark the key values on the charge densities, Electric Field, and potential graphs. (15 pts)

(If you failed to solve part a, do these plots anyway, assuming that each depletion region has a depth of 0.1μm. Please check this box if you opt to use this value: ☐)

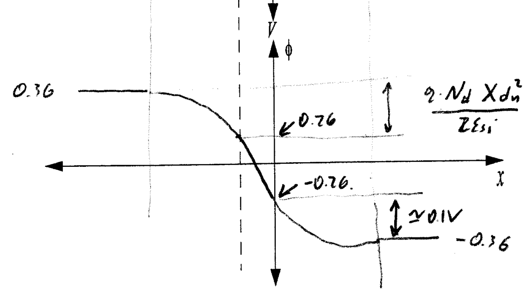


$$E = -\frac{Q}{\varepsilon_{SiO_2}} = \frac{1.6\cdot10^{-3}\,Cb/cm^3 \cdot 0.113\cdot10^{-4}\,cm}{3.45\cdot10^{-13}\,F/cm} = 52.4\cdot10^{3}\,\frac{V}{cm}$$

$$E = -\frac{Q}{\varepsilon_{Si}} = \frac{1.6\cdot10^{-3}\,Cb/cm^3 \cdot 0.113\cdot10^{-4}\,cm}{1.04\cdot10^{-12}\,F/cm} = 17.4\cdot10^{3}\,\frac{V}{cm}$$



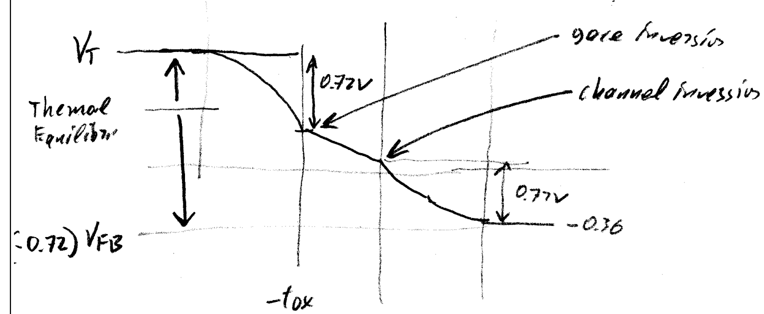
$$\frac{q\cdot N_d\, X_{dn}^2}{2\varepsilon_{Si}} = \frac{1.6\cdot10^{-19}\,Cb \cdot 1\cdot10^{16}/cm^3 \cdot (0.113\,cm\cdot10^{-4})^2}{2\cdot 1.04\cdot10^{-12}\,F/cm} = \simeq 0.1V$$



c. If you apply a positive bias on the gate (i.e. V_{GB}>0), both depletion regions will grow deeper, up to the point where there will be inversion. Because of the concentration symmetry, both the gate and the body will invert at the same time. Calculate the value of V_{GB} needed to bring this device at the onset of inversion. (10 pts)

The flat band (V_{FB}) is $-(\varphi_{pm} - \varphi_n) = -0.72V$

The V_T has to raise the potential in the gate so that:



So, the voltage drop across <u>each</u> depletion region is 0.72V.

$$\Rightarrow \frac{qN_d\cdot X_{dnmax}^2}{2\varepsilon_s} = \frac{qN_a\cdot X_{dpmax}^2}{2\varepsilon_s} = 0.72 \Rightarrow \quad X_{dn} = 3.095\cdot10^{-5}\,cm, \quad X_{dp} = 3.095\cdot10^{-5}\,cm$$

$$\Rightarrow V_T = 0.72V + 0.72V + \frac{Q_{dep}}{C_{ox}} + V_{FB} \quad \Rightarrow \underline{\underline{V_{Tn} = 2.155V}}$$

$$Q_{dep} = 3.095\cdot10^{-5}\,cm \cdot 1.6\cdot10^{-19}\,Cb \cdot 10^{16}/cm^3$$

Problem 3 of 4 (15 points)

The process sequence described below in meant to create a p-channel transistor within a n-well. Follow the steps and draw the two cross sections at the steps indicated (*10 points*):

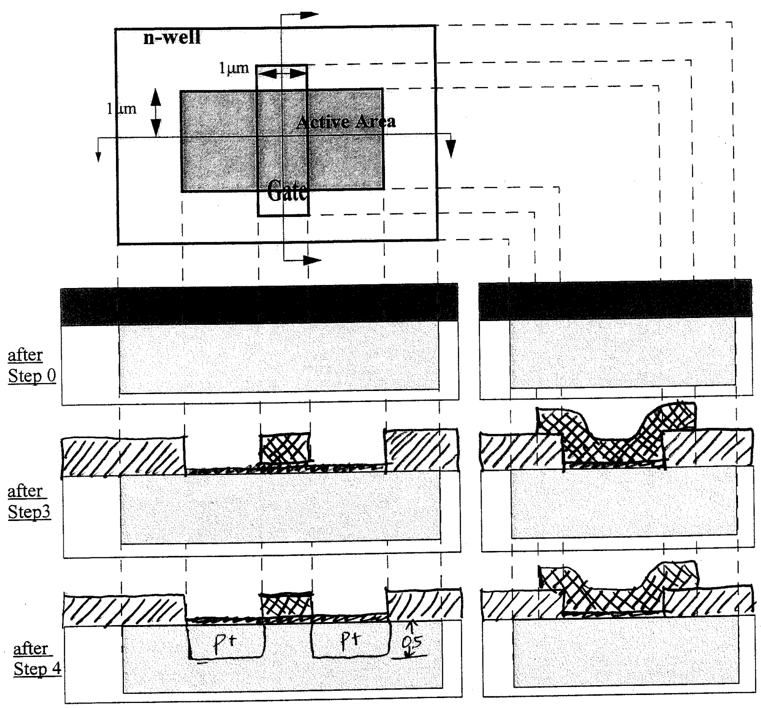
Step 0: Start with the 1μm deep n-well and 0.5μm thick isolation oxide as shown. What is the necessary dose of P (in atoms/cm^2) that is required to achieve a uniform concentration of 10^{16}/cm^3 in the n-well?

Step 1: Remove the 0.5μm of isolation oxide where indicated by the active area mask.

Step 2: Grow 100Angstroms of gate oxide.

Step 3: Deposit and pattern 0.5μm thick polysilicon gate, where indicated by the gate mask.

Step 4: Implant p+ source/drain to a depth of 0.5μm, using a dose of 0.5 10^{15} Boron atoms /cm^2. Calculate the Boron concentration in the source/drain regions.



P dose: = (depth)

$10^{16}/cm^3 \times 1\cdot10^{-4}cm = 10^{12}/cm^2$

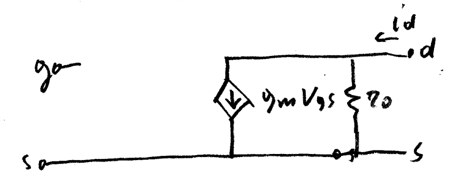
S/D conc:

$\frac{0.5\cdot 10^{15}/cm^2}{0.5\cdot 10^{-4}cm} = 10^{19}/cm^3$

Problem 4 of 4 (15 points)

You are given a n-channel MOS transistor with $\mu_n Cox = 50\mu A/V^2$, V_{Ton}=1.0V, $\lambda n = (0.1/L)V^{-1}$ (L in μm), and ϕp = -0.42V.

a. Draw the small signal model of the MOS transistor in saturation, assuming V_{BS}=0, v_{bs}=0 and ignoring all capacitances.



b. Given that W=10μm, L=10μm, V_{DS}=2V, find the V_{GS} value that will yield a g_m of 50μA/V. Calculate r_o under these conditions. (*Hint: confirm that your solution is such that the transistor is saturated. You can ignore the effect of λ_n in the calculation of g_m*).

$\lambda = \frac{0.1\mu m}{10\mu m} V^{-1} = 0.01 V^{-1}$

$$g_m = \underbrace{\tfrac{1}{2}\mu_n C_{ox}}_{50\mu A/V}\underbrace{\left(\tfrac{W}{L}\right)}_{1}\overbrace{(V_{GS}-V_T)}^{1} = 50\mu A/V \Rightarrow V_{GS} = 2V$$

since $V_{GS} > V_T$ and $V_{DS} > V_{GS} - V_T \Rightarrow$ device saturated.

$$r_o = \frac{1}{\lambda I_D} \qquad I_D = \overbrace{\frac{\mu_n C_{ox}}{2}}^{25\mu A/V}\overbrace{\left(\frac{W}{L}\right)}^{1}\overbrace{(V_{GS}-V_T)^2}^{1V}\overbrace{(1+\lambda V_{DS})}^{\approx 1} \approx 25\mu A$$

$$\Rightarrow r_o \approx \frac{1}{0.01V^{-1}\cdot 25\mu A} = 4\cdot 10^6\,\Omega = 4\,M\Omega$$