Homework Assignment # 11 (Due April 27, Th 8am)

Required Reading
(1) EE143 Lecture Notes
(2) Visit the Device Visualization website http://jas.eng.buffalo.edu/
    Start with http://jas.eng.buffalo.edu/education/mos/mosCap/biasBand10.html
    (a) Run all four simulation of the MOS capacitors (set \( Q_{ox} = 0 \) first and then see effect of \( Q_{ox} \) later.
(b) Run all three MOSFET simulations on http://jas.eng.buffalo.edu/education/mos/mosfet/mosfet.html
(3) EE143 Reader on MOS physics and field effect transistor.
(4) Optional: You can also visit http://inst.eecs.berkeley.edu/~ee130/

Problem 1 Simple threshold voltage calculations
(a) Calculate the threshold voltage of an NMOS transistor when the \( p \)-substrate concentration is \( 2 \times 10^{16} \) cm\(^{-3} \), \( n^+ \) poly-Si is used as the gate material, and a gate oxide thickness of 45nm. Assume there is no body bias and no oxide charges.
(b) Repeat part (a) for a PMOS transistor with \( n \)-substrate concentration = \( 2 \times 10^{16} \) cm\(^{-3} \). Gate material and oxide thickness are the same.

Problem 2 Threshold voltage calculation with Oxide Interface Charge and Threshold Implant
(a) Poly-Si gate (\( n^+ \)) NMOS devices are fabricated with \( 5 \times 10^{15} \) cm\(^{-3} \) boron-doped substrate. Assuming the Si/SiO2 interface charge \( Q_f \) to be \( +3 \times 10^{10} \) q cm\(^{-2} \), find the required gate oxide thickness for \( V_T = +1.0 \) volt.
(b) Phosphorus is implanted through the gate oxide of the NMOS device described in part (a) such that all implanted phosphorus are inside the Si and are localized at Si-SiO\(_2\) interface as a delta-function. Find the implantation dose required to make \( V_T = -2 \) volts.

Problem 3 Threshold implant for CMOS
A p-well CMOS process uses \( n^+ \) poly as the gate material for both the n and p channel devices. The gate oxide thickness is 22nm with no oxide or interface charge. The \( n \)-substrate has a doping concentration of \( 10^{16} \) cm\(^{-3} \) and the \( p \)-well has a doping concentration of \( 2 \times 10^{16} \) cm\(^{-3} \) near the surface region.

A blanket threshold implant step is performed for both the n and p channel devices. (same specie, same dose). Our design goal is to make \( V_{TN} = -V_{TP} \) after the implant. Determine the implant dopant specie AND the required implant dose.
Problem 4 Simple MOSFET I-V Analysis

The $I_D$ versus $V_G$ curves for a n-channel enhancement-mode MOSFET with a small fixed $V_{DS}$ (=50 mV) are shown below. The transistor channel length is 10 µm and the channel width is 100 µm, with a gate oxide thickness of 1000 Å.

(a) Find the threshold voltages for (i) $V_B=0$ and (ii) $V_B=-2$V.
(b) Find the substrate doping concentration (assume the substrate is uniformly doped).
(c) Find the carrier mobility in the channel.
(d) Find $I_{DSat}$ of the transistor for $V_B=0$ and $V_G=10$V.

Problem 5 C-V Analysis

Experimental MOS data of $C/C_{ox}$ versus $V_G$ are given below. It is known that the oxide thickness is 0.26µm, the SiO$_2$-Si interface charge $Q_f = +3.6 \times 10^{11}$q/cm$^2$.

(a) Calculate the maximum depletion layer thickness, $x_{dmax}$
(b) Estimate the substrate doping concentration $N_a$ (ANSWER REQUIRES ITERATION)
(c) Calculate the work function of the gate material.

Problem 6 MOS Narrow Width Effect

For identical channel widths $W$, discuss which one of the following three oxide isolation schemes will exhibit the most narrow width effect: (a) oxide window, (b) LOCOS and (c) trench oxide isolation. Illustrate your answer with sketches or a few sentences. [Note: the cross-sections are along the channel width direction, NOT the channel length direction]
Problem 7 Past exam question

The following cross-section shows a NMOS transistor with n+ poly-Si gate, gate oxide thickness = 200 Å, and a p-substrate with doping concentration = 1E16/cm³.

(a) Thermal SiO2 will have electrical breakdown when the electric field is > 8 \times 10^6 V/cm. What is the maximum $V_G$ that can be applied without causing gate oxide breakdown?

(b) If there is no oxide or oxide interface charge, calculate the threshold voltage $V_T$ for $V_D = 0$.

(c) Calculate the thickness of the depletion region ($x_{d\text{max}}$) underneath the gate oxide when $V_G = V_T$, with $V_D = 0$.

(d) Calculate the drain current for $V_G = V_D = 5$ volts. Use $k = 50 \mu A / V^2$.

Note: $I_{DS}$ (triode region) = $k \left[ (V_G - V_T) \cdot V_D - \frac{V_D^2}{2} \right]$; $I_{DS}$ (saturation region) = $k \left[ (V_G - V_T)^2 / 2 \right]$

(e) If a boron threshold implant is performed with a dose of $10^{12}/cm^2$. What is the new threshold voltage of the transistor. [You can assume the boron implant concentration profile is a delta function located exactly at the Si/SiO2 interface].

(f) What is the drain current for $V_G = V_D = 5$ volts for the MOSFET with the boron threshold implant described in part (e)?

(g) A small-signal C-V measurement across the gate and substrate terminals is performed with the MOSFET structure. $V_D$ is grounded to zero voltage. Sketch qualitatively the C versus $V_G$ curve from −10V to +10V.

(h) Calculate the maximum C value (in F/cm²) and the minimum C value (in F/cm²).