This is a closed book exam. You may use a calculator and the formula sheet at the end of this exam.

There are four equally weighted questions. To receive full credit, you must show your work (scratch paper is attached).

The exam is designed to be taken in 60 minutes, but you may use the full, 75 minute class period.

Be sure to fill in your name and Purdue student ID at the top of the page.

DO NOT open the exam until told to do so, and stop working immediately when time is called.

40 points possible, 10 per question

1) 2 points for each part

2) 2 points for each part

3) 5 points for each part

4) 4a) 2 points  4b) 3 points  4c) 3 points  4d) 2 points
1) Answer the **five multiple choice questions** below by choosing the **one, best answer**.

1a) Assume that there is charge, \( \rho_m(x) \), distributed within the oxide. At what location in the oxide does the charge have the biggest effect on the threshold voltage?
   
a) At the top of the oxide, adjacent to the metal gate.  
b) At the bottom of the oxide, next to the Si substrate.  
c) At the center of the gate oxide.  
d) Charge in the oxide has the same effect wherever it is located.  
e) Charge in the oxide has no effect on the threshold voltage – no matter where it is located.

1b) If the transition from depletion to inversion in an MOS CV characteristic is “stretched out”, what does it indicate?
   
a) A high concentration of mobile ions in the oxide.  
b) A high concentration of fixed charge at the oxide-Si interface.  
c) A large metal-semiconductor workfunction difference.  
d) A high concentration of dangling bonds that change charge state with gate bias.  
e) It translates the \( C(V_G) \) vs. \( V_G \) characteristic to the left or right on the voltage axis.

1c) What is a “donor like” surface state?
   
a) A surface state that is neutral when filled.  
b) A surface state that is neutral when empty.  
c) A surface state that dopes the semiconductor surface n-type.  
d) A surface state cause by the presence of a phosphorus or arsenic atoms on the surface.  
e) A surface state located in energy very near the conduction band.

1d) What is threshold voltage “roll-off”?
   
a) A reduction in the magnitude of the threshold voltage as the channel length decreases.  
b) An effect caused by two-dimensional MOS electrostatics.  
c) A reduction of gate control over the channel potential.  
d) All of the above.  
e) None of the above.

1e) Why are MOSFETs intentionally strained?
   
a) To reduce threshold voltage variations.  
b) To lower the surface state density.  
c) To decrease series resistance.  
d) To increase the channel mobility.  
e) To adjust the gate workfunction.
2) Answer the **five multiple choice questions** below by choosing the **one, best answer**.

2a) What is the “Negative Bias Temperature Instability” (NBTI) of a MOSFET?
   a) A change in threshold voltage due to the breaking of Si-O bonds in P-MOSFETs that occurs under negative gate bias
   b) A change in threshold voltage due to the breaking of Si-O bonds in N-MOSFETs that occurs under negative gate bias
   c) A change in threshold voltage due to the breaking of Si-H bonds in P-MOSFETs that occurs under negative gate bias.
   d) A change in threshold voltage due to the breaking of Si-H bonds in N-MOSFETs that occurs under negative gate bias.
   e) A change in threshold voltage due to the breaking of Si-Si bonds in N-MOSFETs that occurs under negative gate bias.

2b) In NBTI, the number of hydrogen bonds broken varies as time to what power?
   a) one-fourth
   b) one-half
   c) three-fourths
   d) one
   e) five-fourths

2c) The “Anode hole injection model” describes what?
   a) The physical mechanism of NBTI.
   b) The physical mechanism for breaking Si-O bonds in the oxide, which leads to oxide breakdown.
   c) Radiation induced charge build-up due to trapped holes in a MOSFET.
   d) The mechanism for radiation induced gate dielectric rupture.
   e) The movement of mobile sodium ions in the oxide.

2d) What is the most important reliability problem in modern MOSFETs?
   a) Hot carrier injection.
   b) Oxide breakdown.
   c) NBTI in P-MOSFETs
   d) NBTI in N-MOSFETs
   e) Radiation induced damage.

2e) What is a “percolation path” in the context of key MOSFET reliability issues?
   a) A collection of broken bonds in the oxide.
   b) A collection of broken bonds at the Si : SiO$_2$ interface.
   c) A continuous path of broken bonds in the SiO$_2$ from the Si surface to the gate electrode.
   d) A continuous path from source to drain of broken bonds at the Si : SiO$_2$ interface.
   e) A continuous path from source to drain of broken bonds in the Si substrate.
3) This problem concerns the MOS electrostatics of a P-MOS capacitor using the numerical simulation program, MOSCap (https://nanohub.org/tools/moscap) on nanoHUB.org.

The parameters used were for a 45 nm P-MOSFET:
\[ N_A = 2.7 \times 10^{18} \text{ cm}^{-3} \text{ for the bulk doping } \]
\[ x_0 = EOT = 1.2 \text{ nm} \]
\[ Q_F = 0 \]
\[ T = 300 \text{ K} \]
Gate: p+ polysilicon gate with \( (E_V - E_F) = 0.0 \) and no poly depletion.

3a) The plot below is the electrostatic potential vs. position for an applied gate voltage of 0V. From this plot, deduce the following three quantities: i) the flatband voltage, ii) the surface potential (as defined in Pierret), iii) the potential drop across the oxide.
3b) The plot below is the absolute value of the electric vs. position for an applied gate voltage of 0V. From this plot, deduce the following three quantities: i) the electric field in the oxide, ii) the electric field at the Si surface, iii) the width of the depletion region.
4) This question concerns the gate oxide sketched below. Assume that the gate bias is such that it produces a positive electric field, \( E_S \), at the surface of the p-type Si substrate for two different cases. In the first case, i) there is no charge in the oxide or at the oxide : Si interface. In the second case, ii) there is a uniform, positive charge density, \( \rho_{ox}(x) = \rho_1 \text{ C/cm}^3 \), but still no charge at the oxide : Si interface. Assume \( \rho_1 > 0 \).

![Diagram of gate oxide]

4a) For case i) there is no charge in the oxide or at the oxide : Si interface. Derive an expression for the potential drop across the oxide in terms of the electric field at the surface of the Si, \( E_S \) and the parameters of the oxide and the dielectric constant of Si.
4b) Sketch the electric field vs. position in the oxide for two cases: i) there is no charge in the oxide or at the oxide : Si interface, and ii) there is a uniform, positive charge density, \( \rho_{ox}(x) = \rho_1 \text{ C/cm}^3 \) in the oxide, but no charge at the oxide : Si interface. Note that the electric field at the Si surface, \( E(0^+) = E_s \) is indicated on the figure below.

4c) Develop an expression for the potential drop across the oxide for case ii) there is a uniform, positive charge density, \( \rho_{ox}(x) = \rho_1 \text{ C/cm}^3 \) in the oxide, but no charge at the oxide : Si interface. Your answer should be in terms of the electric field at the surface of the Si, \( E_s \) and other relevant parameters.
4d) Explain qualitatively what happens to the threshold voltage when there is a positive charge in the oxide. Does it increase, decrease, or stay the same? Explain with an equation and in words.
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