Problem 1: 10 Points Possible _________

Problem 2: 20 Points Possible _________

Problem 3: 10 Points Possible _________

Problem 4: 20 Points Possible _________

Problem 5: 20 Points Possible _________

Problem 6: 20 Points Possible _________

TOTAL: 100 Points Possible _________
Problem 1: 10 Points

Fill in the blanks to correctly complete the sentences.

To improve conduction in silicon, atoms from other elements are incorporated into the lattice.

The addition of Group III elements creates ___p____ - type material.

For example, ______boron______ is a Group III element that might be added to the silicon.

The addition of Group V elements creates ___n____ - type material.

For example, ___phosphorus___ is a Group V element that might be added to the silicon.

The Group ____III_____ elements need one more electron in the outer shell to complete all four lattice bonds.

This lack of an electron is called a _____hole______.

When the two types of material are joined together, electrons cross the junction between the two materials to complete lattice bonds where needed.

The movement of free electrons from an area of greater concentration to lesser concentration, motivated by the need to complete lattice bonds, is called ___diffusion_____________

This creates a layer without free charge carriers, called the ____depletion___________ layer.

The movement of electrons creates positive charge in the atoms the electrons have left behind, and negative charge in the atoms which the electrons have joined. This creates a potential difference across the junction; the ____n____ - type material is at higher potential.

This causes electrons to move across the junction towards the higher electric potential. This movement, due to attraction by positive potential, is called ______drift_____________.
Problem 2: 20 Points

Determine the logical operation performed by the circuit below (copied 4 times for convenience):
Problem 3: 10 Points

Consider the following circuit, with the input voltage just below $V_{DD} - V_T$. Here, the NMOS threshold voltage is $V_T$ and the PMOS threshold voltage is $-V_T$. $V_T$ is positive, and much smaller than $V_{DD}$. Assume that the transistors have matched $I_D/V_{DS}$ characteristics.

Determine the most likely mode of operation for each transistor.

PMOS:

\[ V_{GS(P)} = V_{DD} - V_T - \varepsilon - V_{DD} = -V_T - \varepsilon \]

$V_{GS(P)}$ is near threshold, so transistor is barely turned on $\Rightarrow$ shallow curve $\Rightarrow$ small $I_D$

NMOS:

\[ V_{GS(N)} = V_{DD} - V_T - \varepsilon \]

$V_{GS(N)}$ is well above threshold, so transistor is fully turned on $\Rightarrow$ steep curve

Small $I_D$ (from PMOS) and steep curve $\Rightarrow V_{DS(N)}$ small $\Rightarrow$ NMOS in triode

$V_{DS(N)}$ small $\Rightarrow$ $V_{DS(P)}$ not small $\Rightarrow$ PMOS in saturation
**Problem 4:** 20 Points

Consider the following circuit. Find $V_{OUT}$ when $V_{IN}$ is 3.7 V.

**NMOS:**

$V_{T(N)} = 1 \text{ V}$

$\lambda = 0$

$I_{DSAT(N)} = 10^{-3}(V_{GS(N)}-V_{T(N)})^2 \text{ A}$

**PMOS:**

$V_{T(P)} = -1 \text{ V}$

$\lambda = 0$

$I_{DSAT(P)} = -10^{-3}(V_{GS(P)}-V_{T(P)})^2 \text{ A}$

$I_{D(P)} + I_{D(N)} = 0$

$V_{DS(N)} - V_{DS(P)} = 5 \text{ V}$

Guess that PMOS is in saturation and NMOS is in triode (basically situation from Problem 3).

**PMOS:**

$I_{D(P)} = I_{DSAT(P)}(1+\lambda V_{DS(P)}) = -10^{-3}(V_{GS(P)}-V_{T(P)})^2 = -10^{-3}(5 - 3.7 - -1)^2 = -9 \times 10^{-5} \text{ A}$

**NMOS:**

$I_{D(N)} = 2 I_{DSAT(P)} (V_{GS(N)}-V_{T(N)}-V_{DS(N)/2})V_{DS(N)} / (V_{GS(N)} - V_{T(N)})^2 = 2 \times 10^{-3} (3.7 - 1 - V_{DS(N)/2})V_{DS(N)}$

$= -10^{-3}V_{DS(N)}^2 + 5.4 \times 10^{-3} V_{DS(N)}$

$= -I_{D(P)} = 9 \times 10^{-5}$

Roots of $-10^{-3}V_{DS(N)}^2 + 5.4 \times 10^{-3} V_{DS(N)} - 9 \times 10^{-5}$: $V_{DS(N)} = 5.383 \text{ V}$ and $0.017 \text{ V}$

$V_{DS(N)} = 5.383 \text{ V}$ impossible, so $V_{DS(N)} = 0.017 \text{ V} = V_{OUT}$

$V_{DS(N)} = 0.017 \text{ V}$ agrees with triode mode & $V_{DS(P)} = 0.017 - 5 = -4.983 \text{ V}$ agrees with saturation
Name: Solutions

Problem 5: 20 Points

Consider the following circuit. Find $V_{OUT}$ when $V_{IN}$ is 3.7 V.

**NMOS:**

$V_{T(N)} = 1$ V

$\lambda = 0$

$I_{DSAT(N)} = 10^{-3}(V_{GS(N)} - V_{T(N)})^2$ A

**PMOS:**

$V_{T(P)} = -1$ V

$\lambda = 0$

$I_{DSAT(P)} = -10^{-3}(V_{GS(P)} - V_{T(P)})^2$ A

$I_{D(P)} + I_{D(N)} + \frac{V_{DS(N)}}{1000} = 0$

$V_{DS(N)} - V_{DS(P)} = 5$ V

Guess that PMOS is in saturation and NMOS is in triode (keep guess from Problem 4).

**PMOS:**

$I_{D(P)} = I_{DSAT(P)}(1 + \lambda V_{DS(P)}) = -10^{-3}(V_{GS(P)} - V_{T(P)})^2 = -10^{-3}(5 - 3.7 - -1)^2 = -9 \times 10^{-5}$ A

**NMOS:**

$I_{D(N)} = 2I_{DSAT(P)}(V_{GS(N)} - V_{T(N)} - V_{DS(N)/2})V_{DS(N)} / (V_{GS(N)} - V_{T(N)})^2 = 2 \times 10^{-3}(3.7 - 1 - V_{DS(N)/2})V_{DS(N)}$

$= -10^{-3}V_{DS(N)^2} + 5.4 \times 10^{-3}V_{DS(N)}$

$= -I_{D(P)} \cdot V_{DS(N)} / 1000 = 9 \times 10^{-5} - 10^{-3}V_{DS(N)}$

Roots of $-10^{-3}V_{DS(N)^2} + 6.4 \times 10^{-3}V_{DS(N)} - 9 \times 10^{-5}$: $V_{DS(N)} = 6.386$ V and $0.014$ V

$V_{DS(N)} = 6.386$ V impossible, so $V_{DS(N)} = 0.014$ V = $V_{OUT}$

$V_{DS(N)} = 0.014$ V agrees with triode mode & $V_{DS(P)} = 0.014 - 5 = -4.986$ V agrees with saturation
Problem 6: 20 Points

Sketch $V_{OUT}(t)$ for the diode circuit

a) using the ideal model
b) using the large-signal model
c) using the small-signal model.

Provide enough detail to completely indicate the effect created by the circuit.

Ideal model: neither diode can accept positive forward voltage.

Large-signal model: each diode can accept any forward voltage up to 0.7 V, acting like open circuit. Above 0.7, a diode conducts current and resistor takes rest of input voltage.
Problem 6 Workspace

Small signal model: each diode acts as open circuit for forward voltage up to 0.6 V. Above 0.6, a diode conducts current through the 20 Ω resistor and its own 20 Ω resistance (part of its model). The difference between the input and 0.6 V is distributed across the 20 Ω resistors; thus the diode gets 0.6 V plus half the difference between 0.6 and the input voltage.