1) The purpose of this exercise is to help you review the basic theory of the MOSFET, introduce you to some key device parameters, and give you a feel for the typical values of key device performance metrics for state-of-the-art MOSFETs.

**Step 1:** View the online presentation: “A Review of MOSFET Fundamentals,” by Mark Lundstrom. This online lecture is available at nanoHUB.org at [https://www.nanohub.org/resources/5307](https://www.nanohub.org/resources/5307) (Viewing this lecture is also a good way to study for Exam 6.)

**Step 2:** For the exercises below, you will need to run the simulation program, nano-CMOS, on nanoHUB.org. Be sure you have an account, then proceed with the exercises below.

Locate the simulation tool, nano-CMOS ([https://nanohub.org/tools/nanocmos](https://nanohub.org/tools/nanocmos)), and use it to examine the IV characteristics of “45nm” N-channel CMOS technology. Select “NMOS 45nm,” and use the default values. Push the “Simulate” button, and then answer the following questions.

(You should clearly describe how you obtain each parameter. Note that you are able to change the minimum and maximum axes scales and to select either linear or logarithmic scales.)

1a) Determine the on-current in µA/µm
1b) Determine the off-current in µA/µm
1c) Determine the subthreshold swing, $S$, in mV/decade
1d) Estimate $V_{DSAT}$ for $V_{GS} = 1.0V$. (Do not simply “eyeball” the answer; develop a simple methodology so that another person who follows it would get the same answer.
1e) Estimate the DIBL in mV/V
1f) Estimate $V_T(\text{lin})$ and $V_T(\text{sat})$ in V
1g) Estimate the output resistance, $R_0$, in $\Omega$-µm for $V_G = V_{DD}$
1h) Estimate the channel resistance, $R_{CH}$, in $\Omega$-µm for $V_G = V_{DD}$
1i) Estimate the transconductance, $g_m$, in mS/mm at the maximum gate (and drain) voltage.
1j) The “self-gain”, $A = g_m R_0$ is often used as a metric for analog applications (it is roughly the maximum small signal gain that could be achieved in an amplifier circuit with this transistor). Estimate the self-gain for this transistor.
HW Week 15 continued

**Additional Exercise:** Repeat problem 1) for a p-channel MOSFET by selecting “PMOS 45nm,” and pushing the “Simulate” button. You should use the default values. Estimate all of the device parameters listed problem 1) for this PMOS transistor. Discuss the main difference that you see.

2) The purpose of the following two exercises below is to review MOS electrostatics using the numerical simulation program, MOSCap (https://nanohub.org/tools/moscap) on nanoHUB.org.

Use the same parameters we used for the 45nm N-MOSFET in 1):

- $N_A = 2.7 \times 10^{18} \text{ cm}^{-3}$ for the bulk doping
- $x_0 = EOT = 1.1 \text{ nm}$
- $Q_F = 0$ $Q_F = 0.0$
- $T = 300 \text{ K}$
- $V_{DD} = 1.0 \text{ V}$

Assume an n$^+$ polysilicon gate with $(E_F - E_C) = 0.0$ and ignore poly depletion.

2a) Determine the following quantities by analytical calculations (assume $V_G = 0 \text{ V}$). You should use the delta-depletion approximation for these calculations.

(The first thing that a prudent engineer does when using a new simulation program is to check the results to be sure that he or she using the program properly and that the program is producing correct results – at least for one problem similar to the problem of interest. Good engineers take responsibility to be sure that a simulation tool is producing correct results for their problem. In question 3), we will run MOSCap and compare answers to the analytical results.)

(i) The flatband voltage, $V_{FB}$
(ii) The surface potential, $\phi_S$
(iii) The electric field in the oxide, $E_{ox}$
(iv) The electric field in the silicon at the surface, $E_{Si}$
(v) The depletion region depth, $W_D$
(vi) The charge in the silicon, $Q_S$
(vii) The charge on the gate, $Q_G$
(viii) The voltage drop across the oxide, $\Delta \phi_{ox}$
(ix) The threshold voltage for this MOS capacitor, $V_T$
2b) Simulate the above MOS capacitor using MOSCap on the nanoHUB. Use the same p-type doping and gate oxide thickness as in problem (1), and a voltage range of 2V to -4V. You can answer the following questions by reading the data from the MOSCap plots or by downloading the data as text. From the results, deduce the following quantities:

(i) The flatband voltage, $V_{FB}$ (HINT: Deduce this from the $V_G = 0$ results.)

(ii) The surface potential, $\phi_S$ (as defined in the text – be careful MOSCap does not use the same reference potential as Taur and Ning. That is, $\phi$ is not 0 in the bulk.)

(iii) The electric field in the oxide, $E_{ox}$

(iv) The electric field in the silicon at the surface, $E_{Si}$

(v) The depletion region depth, $W_D$

(vi) The charge in the silicon, $Q_S$

(vii) The charge on the gate, $Q_G$

(viii) The voltage drop across the oxide, $\Delta \phi_{ox}$

(ix) The threshold voltage for this MOS capacitor, $V_T$

Explain how you deduced these parameters, and compare them to the values in part 2a). Some of these values will not be given directly by MOSCap – you will have to deduce them from the results that are given.