Problems for Chapter 4 of 'Ultra Low Power Bioelectronics'

Problem 4.1

This problem investigates the source-follower shown in Figure P4.1. We shall use body-referenced transistor models throughout the problem. Assume that the two transistors are perfectly matched with identical parameters and that the bulk is connected to ground; $\kappa_0 = 0.7$, $V_{TO} = 1.0$ V, $\phi_0 = 1.0$ V, $V_{DD} = 5$ V, $V_1 = 0.7$ V, and $V_2 = 2$ V.

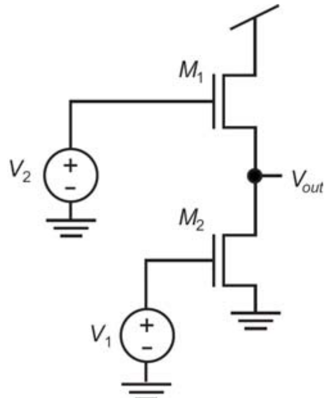

Figure P4.1 Source follower for Problems 4.1 and 4.2.

a) Assuming that all the transistors are in saturation, what is the value of V_{OUT}? Prove that all transistors are in saturation.
b) Using the definition of κ, estimate Ψ_S, the surface potential of M_1.
c) Plot the mobile charge per unit area, $Q_I(x)$, in M_1, as we go from the source, $x = 0$, to the drain, $x = L$. You will need to get the shape correct, but you do not need to evaluate $Q_I(0)$ quantitatively.

Problem 4.2

In this problem, we will use the circuit shown in Figure P4.1 and the parameters listed in Problem 4.1; however, for this problem we shall set $V_1 = 1.3$ V. Use body-referenced transistor models throughout the problem.

a) What is the new value for V_{OUT}? Prove that all transistors are still in saturation.
b) Draw a qualitative plot of transistor M_1, showing the widths of all depletion regions, source, drain, and gate. You do not need to get quantitative accuracy but your plot should have the right qualitative features.
c) What is the value of the surface potential, $\Psi_S(0)$, at the source of transistor M_1?
d) What is the value of the surface potential, $\Psi_S(L)$, at the drain of transistor M_1?

Problem 4.3

Figure P4.3 shows a transistor circuit. With respect to this circuit, you are given the following parameters: $V_{DD} = 3$ V, $I_{BIAS} = 50$ nA, $\phi_t = 25$ mV, $\kappa_p = \kappa_n = 0.75$, $|V_{Tp}| = V_{Tn} = 0.9$ V, $|\phi_0| = 1.0$ V, $\mu_p C_{ox} = \mu_n C_{ox} = 40\ \mu\text{A/V}^2$, W/L=2 for all NMOS transistors, while the W/L of PMOS transistors is 1 unless otherwise stated. C_{BIG} is large enough such that it may be considered a short circuit at the ac frequencies of interest. Use body-referenced transistor models throughout the problem.

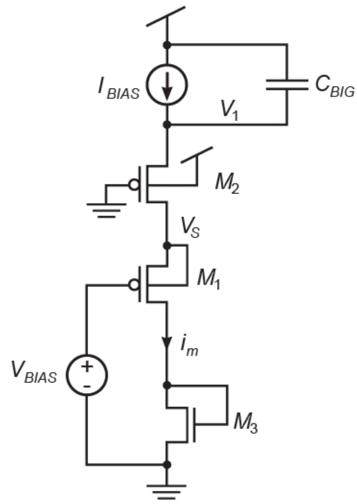

Figure P4.3 Circuit schematic for Problems 4.3 and 4.4

a) Given that $I_0 = 10^{-18}$ A, that M_1 operates in subthreshold, and that V_{BIAS} is set such that M_1 is saturated, determine V_{SG} for M_1.
b) Suppose that we desire $V_S = 2.7$ V. Using your answer from part a), determine V_{BIAS}.
c) Determine V_{DS} for M_1.

Problem 4.4

In this problem we will use the circuit shown in Figure P4.3 again with the parameters given in problem 4.3. Suppose $V_{SD} = 100$ mV for M_2 and that the body effect is negligible. Assume that $V_S = 2.7$ V and that body-referenced transistor models are accurate.

a) In what region of inversion does M_2 operate? Justify.
b) Is it saturated? Justify.
c) Determine the W/L for M_2.
d) Sketch the surface potential of M_2 along the entire length of its channel. You should specify the values of the surface potential at the drain and at the source.

Problem 4.5

From Figure 3.4 and the intuition of the diode-clamp approximation, provide a *physical* argument for why the second-line of Equation (4.42) must follow from the first line of Equation (4.42).

Problem 4.6

a) From the Einstein relation, the fundamental equations of drift and diffusion (Equation (3.19)), and the charge profile of transistors in saturation, show that Equation (4.28) has the following physical interpretation: When the inversion charge is large enough to cause the surface potential at the source to change from its subthreshold value by $2\phi_t$, thus establishing a significant lateral electric field from drain to source, the drift current just dominates over the diffusion current.

b) Provide an intuitive explanation for why the change is $2\phi_t$ rather than ϕ_t as might naively be expected from the relationship between drift and diffusion in Equation (3.19).

c) Relate this threshold amount of inversion charge at the border between weak inversion and strong inversion to the pre-constant of the empirical EKV model of Equations (4.47) and (4.48).

Problem 4.7

Design an experiment that will allow you to use subthreshold and above-threshold measurements to estimate γ and ϕ_0 for a transistor.

Problem 4.8

a) If the depletion capacitance in a MOSFET were completely linear (no square-root dependence for any set of terminal voltages) would the MOSFET still exhibit a body effect? If so, what quantitative equation in the text would model this effect?

b) In this linear-depletion-capacitance case, would there be any advantage to having separate source-referenced and body-referenced models?

c) In a certain fully-depleted silicon-on-insulator transistor, the depletion-region depth is at a maximum value and this depth is invariant to changes in surface potential in all regimes of operation. Would such a transistor exhibit a body effect? What would the value of κ be in such a transistor?

Problem 4.9

This problem requires the use of a circuit simulator such as SPICE. In this problem we will use SPICE to generate plots of I_D vs. V_{DS} of an NMOS transistor with W = 4.95 µm and L = 2.55 µm for different V_{GS} and V_{SB} voltages.

a) Set V_{SB} = 0 V and V_{GS} = 1 V. Vary V_{DS} from 0 V to 5 V in increments of 0.1 V and measure the drain current. Repeat the measurement for V_{GS} = 1 V, 2 V, 3 V, 4 V, and 5 V. Plot all curves in the same graph.

b) Repeat the measurement from part a), but this time set V_{SB} = 2.5 V. How does the result differ from the one in part a)?

Problem 4.10

Prove that, under appropriate limiting conditions, the body-referenced equation and source-referenced equation of the empirical EKV model (Equations (4.47) and (4.48) respectively) lead to the corresponding body-referenced and source-referenced strong-inversion equations listed in Table 4.1.