Homework #8 - EE 482

due **Friday** 3/11/11

1. An n-channel silicon MOS transistor with a polysilicon gate doped to the edge of degeneracy with phosphorus ($E_f = E_c$) has doping of $N_a = 10^{18}\text{cm}^{-3}$ in the substrate, $x_{ox} = 4\,\text{nm}$ and $W = 2L = 1.0\mu\text{m}$. Assume oxide charges can be ignored.

   (a) Find the threshold voltage with $V_{SB} = 0$.

   (b) Calculate α, the correction term for change in depletion charge as V_{CB} increases, in the improved square-law drain current equation:

   $$I_D = \frac{W}{L}\mu_n' C_{ox}'\left[(V_{GS} - V_T)V_{DS} - \frac{(1+\alpha)V_{DS}^2}{2}\right]$$

   An appropriate value is $\alpha = (1/C_{ox})(dQ_d^{max}/V_{CB}) = C_s^{depl}/C_{ox}$ determined near threshold with $V_{CB} = 0$.

   (c) Plot I_{DS} versus V_{DS} for $V_{GS} = 3V$ and $V_{SB} = 0$ using the three linear-region drain current equations ($\alpha = 0$, α as above, and Eq. (9) in notes). Include V_{DS} values at least up to saturation.

   (d) Using the linearized equation and α as calculated, determine the operating regime and drain current under the following conditions. In each case, sketch the band diagram at the drain end of the channel.

      i. $V_S = 0$, $V_B = 0V$, $V_G = 3V$, $V_D = 1V$.

      ii. $V_S = 0$, $V_B = 0V$, $V_G = 3V$, $V_D = 3V$.

      iii. $V_S = 0$, $V_B = 0V$, $V_G = 0V$, $V_D = 3V$.

2. A p-channel (n-type substrate) MOS transistor has a threshold voltage of -0.4V. The source and substrate are grounded. The gate is biased at -3V and the drain at -2V. The oxide thickness is 10 nm, the substrate doping is $N_d = 10^{17}\text{cm}^{-3}$ and $W/L = 2$.

   (a) Calculate the flatband voltage.

   (b) What mode (cutoff, linear, saturated, etc.) is the transistor operating in? Consider the change in depletion charge due to drain bias.

   (c) How much drain current is flowing (ignore channel length modulation)?

   (d) How large a positive substrate bias (V_{BS}) would be required to change the operating mode of the device keeping all other biasing the same? What would the new mode be?

   (e) If this transistor was implanted with a shallow dose of donors with a total dose of 10^{12}cm^{-2}, what would the new threshold voltage be ($V_{SB} = 0$). If the biasing remained the same, in what mode would the implanted device operate?

3. What is the output resistance of an n-channel silicon MOS transistor due to channel length modulation for $\Delta L \ll L = 0.1\mu\text{m}$ if $V_{DS} = V_{DS\text{sat}} + 0.4V$, $I_D = 1.0\,\mu\text{A}$ and $N_a = 2\times10^{18}\text{cm}^{-3}$.

4. An npn transistor has neutral region widths of $x_E = 0.1\mu\text{m}, x_B = 0.05\mu\text{m}$ and $x_C = 0.5\mu\text{m}$, and doping of $N_{dE} = 2\times10^{20}\text{cm}^{-3}$, $N_{aB} = 5\times10^{18}\text{cm}^{-3}$ and $N_{dC} = 5\times10^{17}\text{cm}^{-3}$. Assume that in all regions the minority carrier lifetimes are 0.5μs.

   (a) Determine I_{ES} and α_F ($|I_C/I_E|$) for forward operation (base-emitter junction forward biased, base-collector junction unbiased or reverse biased). Assume that recombination in the base and depletion regions can be ignored ($\alpha_F = \gamma_F$). Use this value to determine β_F.

   (b) Determine I_{CS} α_R ($|I_E/I_C|$) for reverse operation (base-emitter junction unbiased or reverse biased, base-collector junction forward biased). Assume that recombination in the base and depletion regions can be ignored ($\alpha_R = \gamma_R$). Use this value to determine β_R.

   (c) For the bias conditions of (a) and (b), sketch the minority charge densities and current densities as functions of position from emitter to collector. Assume the diode which is off is reversed biased by at least a few kT.

   (d) If $A_E = A_C = 10^{-5}\text{cm}^2$, find the collector current (I_C) if $I_B = 1\mu A$ and $V_{CE} = 3\,\text{V}$. Hint: Estimate whether the base-emitter and base-collector junctions are forward or reverse biased and use that information to help simplify the analysis if possible. (Diode reverse leakage current can generally be neglected.)