ECE 3030: Physical Foundations of Computer Engineering
Spring 2024
Homework 6—Total points 100
Due on Thursday 4/10/2024 at 11.59am. In case of a late submission, you will be penalized by 50 points for each day after the submission deadline has passed. You will receive no score if you submit after the solution has been posted.

Q1 The square law model with correction for subthreshold current relating the drain current I_D, the drain voltage V_D and the gate voltage V_G in a long-channel MOSFET is as follows.

$$\frac{I_D}{W} = \begin{cases} I_{sub-V_t} e^{\frac{q(V_G - V_t)}{mkT}} (1 - e^{\frac{-qV_D}{kT}}); \text{ when } V_G < V_t \text{ (sub-threshold)} \\ I_{sub-V_t}(1 - e^{\frac{-qV_D}{kT}}) + \mu C_{ox} \frac{1}{L}((V_G - V_t)V_D - \frac{1}{2}V_D^2); \text{ when } V_G - V_t > V_D \text{ (linear)} \\ I_{sub-V_t}(1 - e^{\frac{-qV_D}{kT}}) + \mu C_{ox} \frac{1}{2L}(V_G - V_t)^2; \text{ when } V_G - V_t < V_D \text{ (saturation)} \end{cases}$$

We have also defined the on-current I_{ON} and the off-current I_{OFF} as follows.

$$\begin{aligned} I_{ON} &= I_D(V_G = V_D = V_{DD}) \\ I_{OFF} &= I_D(V_G = 0, V_D = V_{DD}) \end{aligned}$$

Here, V_{DD} is the power supply voltage, and $qV_{DD} >> kT$.

Q1.1 Based on these relations, find expressions for I_{ON} and I_{OFF} in terms of V_{DD}, V_t, I_{sub-V_t}, μ, C_{ox}, W and L. Note that when $V_G = V_D = V_{DD}$, the MOSFET operates in the saturation region. [25 pts]

Q1.2 Based on the derived expressions, find how I_{ON} and I_{OFF} would change if V_t is increased. [25 pts]

Q2 Consider an n-type MOSFET with N_A=7×10^{18} m^3. The gate length of the MOSFET L=2 μm, width W=12 μm and the oxide thickness t_{ox}= 8 nm. Take N_C=N_V=10^{25} m^{-3}, E_G=1.12 eV, n_i=1.5×10^{16} m^{-3}, kT=0.026 eV, vacuum permittivity $\varepsilon_\circ$=8.854×10^{-12} F/m, dielectric constant of oxide ε_{ox}=4, dielectric constant of silicon ε_{Si}=12, electron mobility μ_n=230×10^{-4} m^2/Vs, hole mobility μ_p=83 ×10^{-4} m^2/Vs.

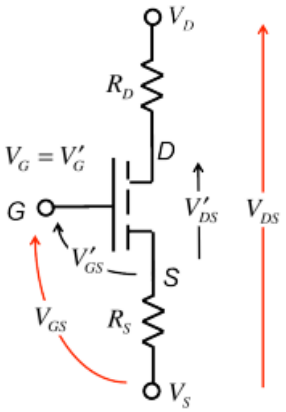
(Q2.1) Calculate $\phi_B = |E_F - E_i|$, the oxide capacitance C_{ox}, the maximum depletion width W_{max} and the threshold voltage V_t. [5 pts]

(Q2.2) Calculate the drain current I_D for the following six cases. [45 pts]

1. V_G=3 V, V_D=2 V.

2. V_G=0.2 V, V_D=1 V.
3. V_G=2.2 V, V_D=2 V.
4. V_G=2 V, V_D=1 V.
5. V_G=0.5 V, V_D=0.5 V.
6. V_G=1.5 V, V_D=2 V.

Q3 Real transistors have parasitic series resistances at the source and drain. As shown in the figure below, the result is that the voltages applied to the terminals of the device are not the voltages on the terminals of the intrinsic device. Modify the square law MOSFET equations to include the effects of source and drain series resistances.



Prob. 3 Figure.