5. (15 points, 3 points each) 1. The energy band diagram for a $p$-Si/SiO$_2$/n-Si capacitor (SOS-C) under flat-band conditions is given below. The SOS-C is ideal except for a non-zero work function difference. $T = 300$ K, $N_A$ (p-side) = $N_D$ (n-side) = $10^{15}$ cm$^{-3}$, $n_i$ = $10^{10}$ cm$^{-3}$, oxide thickness = $5 \times 10^{-6}$ cm, and area $A_G = 10^{-3}$ cm$^2$.

(a) To achieve the pictured state, there must of course be a non-zero voltage applied to the SOS-C gate. What is it? Give both the polarity and magnitude of $V_G$. Give both a symbolic and numerical answer.

(b) Sketch the energy band diagram and the associated block charge diagram for the SOS-C when a large positive gate voltage (say $V_G > 5$V) is applied to the device.

(c) Same as (b) except now a large negative voltage is applied to the gate.
(d) Make a sketch of the high-frequency $C-V_G$ characteristic to be expected. Explain how you arrived at your sketch.

(e) Determine the minimum capacitance exhibited by the device. Give both a symbolic and numerical answer.
(9 points, 3 points each) 2. Apply constant-field scaling to the ideal current-voltage relations of MOSFETs in both the saturation and non-saturation bias region. Assume the scaling factor \( k = 0.6 \), e.g., the new gate length \( L \) is now 0.6 \( L \).

(a) How does the drain current scale in each bias region? Explain.

(b) How does the power dissipation per device scale in each bias region? Explain.

(c) Why is it important to develop “high \( \kappa \)” dielectric material to replace SiO\(_2\)? \( \kappa \) here means dielectric constant (not the \( k \) above).

\[ C = \frac{\kappa}{d}. \] The ultimate limit of \( d \) is one or two atomic layers, and the practical limit to have a continuous film may be several times higher. If \( \kappa \) is high, \( d \) can be thicker, which is more practical.

\[ \begin{align*}
I_p &= \frac{1}{2} \mu_c C_{ox} \left( \frac{W}{L} \right) \left[ 2(V_{gs} - V_t) V_{ds} - V_{ds}^2 \right] \\
&= \frac{1}{2} \mu_c C_{ox} \left( \frac{kW}{kL} \right) \left[ 2(kV_{gs} - V_t) kV_{ds} - (kV_{ds})^2 \right] \\
&\approx k \frac{1}{2} \mu_c C_{ox} \left( \frac{kW}{kL} \right) \left[ 2(kV_{gs} - V_t) kV_{ds} - (kV_{ds})^2 \right]
\end{align*} \]

In the saturation region

\[ \begin{align*}
I_p &= \frac{1}{2} \mu_c C_{ox} \left( \frac{kW}{kL} \right) \left[ kV_{gs} - V_t \right]^2 \\
&\approx k \frac{1}{2} \mu_c C_{ox} \left( \frac{kW}{kL} \right) \left[ kV_{gs} - V_t \right]^2
\end{align*} \]

(b) \( P = I_d V_{gs} \Rightarrow (kI_d)(kV_{gs}) \Rightarrow k^3 P \)