1) Assume the square law theory of the MOSFET:

\[
I_D = \frac{W \mu_n C_{ox}}{L} \left[ (V_G - V_T) V_D - \frac{V_D^2}{2} \right] \quad 0 \leq V_D < V_{Dsat} \quad V_G \geq V_T
\]

\[
I_D = \frac{W \mu_n C_{ox}}{2L} (V_G - V_T)^2 \quad V_D \geq V_{Dsat} \quad V_G \geq V_T
\]

1a) Derive an expression for the electric field vs. position along the channel in the linear region of operation.

1b) Derive an expression for the electric field vs. position along the channel at \( V_D = V_{Dsat} \).

2) An equilibrium energy band diagram for a p-channel MOSFET is shown below. Draw an energy band diagram for a p-channel MOSFET for \( V_{GS} \ll 0 \) and for \( V_{DS} \ll 0 \). The source and drain are heavily doped p-type, and the channel is moderately doped n-type.

![Energy Band Diagram](image)

3) 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.
4) The series resistances affect the drain current differently in the linear and the saturation regions. Explain how $R_s$ and $R_D$ affect the linear region drain current and the saturation region drain current.

5) Measured IV data for an n-channel MOSFET are shown below. Relevant parameters for this MOSFET are:

- $T = 300$ K
- Oxide thickness: $x_0 = 1.7$ nm
- Relative dielectric constant: $\kappa_{ox} = 4$
- Power supply voltage: $V_{DD} = 1.2$ V
- Series resistances: $R_s = R_D = 100 \, \Omega - \mu m$
- $I_{ON} = 1120 \, (\mu A/\mu m)$

![Prob. 3 Figure](image)

$R_{CH} = \frac{V_{DS}}{I_D} = 340 \, (\Omega - \mu m)$

Prob. 3 Figure $I_D$ vs. $V_{DS}$
Answer the following questions:

5a) From the so-called “on-current”, $I_D \left(V_{SD} = V_{DD}, V_{DS} = V_{DD}\right)$, estimate the average velocity of electrons in the channel at the source end of the channel.

5b) From the linear region of operation, estimate the effective mobility of this MOSFET.

6) Consider an n-channel MOSFET with the following parameters:

\[ N_A = 10^{18} \text{ cm}^{-3} \]

$n^+$ polysilicon gate electrode (with $E_F = E_C$)

oxide thickness: $x_0 = 1.5 \text{ nm}$

$T = 300 \text{ K}$

6a) What is the threshold voltage for this MOSFET?

6b) What is the magnitude of the electric field in the oxide for $V_G = 1 \text{ V}$?