Question 1 [19 marks]:
Figure 1 shows transfer characteristics of a field-effect transistor (FET), measured at applied drain voltages of $V_D = 10V$, $V_D = 40V$. The transistor width and length are $W = 1$ mm and $L = 50 \mu m$, respectively. The gate oxide capacitance is 11 nFcm$^{-2}$. This data is available to download [here](#).

![Figure 1](#) Transfer characteristics ($I_D$ vs $V_G$) of an example field-effect transistor. This data is available to download [here](#).

a) By numerically differentiating the data when $V_D = 10V$, evaluate the representative linear field effect mobility for this data. Show all the steps and explain the rationale for your choice of value of $\mu_{\text{lin}}$. For this analysis assume that threshold voltage is close to $V_T = 0V$. [7 marks]

The data can be differentiated, as described in class, using 3-point differentiation. In this process we lose the first and final data point.
We just need to identify what voltages are appropriate for the so-called linear regime. For the approximation to be valid we must only consider data where: \(|V_D| \ll |V_G - V_T|\). We are told that we can assume the threshold voltage is \(V_T \approx 0\) V, hence we can consider data points where \(V_G \gg V_D\). I have here taken the average of the derivative for \(V_G > 40\) V:

\[
\frac{dI_D}{dV_G} = 6.76 \times 10^{-6} \text{ A/V}
\]

Now we just put the constants in to our equation to evaluate the mobility:

\[
\mu_{\text{lin}} = \frac{L}{W C_{\alpha x} V_D} \frac{dI_D}{dV_G}
\]

We can keep the channel dimensions in microns, since \(W/L\) is just a ratio. And we can keep the capacitance in \(\text{F/cm}^2\), as the final result will be in \(\text{cm}^2/\text{Vs}\).

\[
\mu_{\text{lin}} = \frac{50}{1000 \times 11 \times 10^{-9} \times 10} \times 6.76 \times 10^{-6}
\]

\[
\mu_{\text{lin}} = 3.07 \text{ cm}^2/\text{Vs}
\]

b) By using either of the approaches described in class, use the data when \(V_D = 40\) V to determine a representative saturation field-effect mobility. Show all the steps and explain the rationale for you choice of value of \(\mu_{\text{sat}}\). For this analysis assume that threshold voltage is close to \(V_T = 0\) V. [6 marks]

The first approach is to take the square root of the drain current, then differentiate that with respect to gate voltage:

In the saturation regime we require \(|V_D| \gg |V_G - V_T|\). We are told that \(V_G \approx 0\), therefore we can extract values from the graph if \(V_D \geq V_G\). For saturation-regime we also require that the device is “on”. I have here chosen an average of values between \(10V \leq V_G \leq 20V\):
\[ \frac{d\sqrt{I_D}}{dV_G} = 4.79 \times 10^{-4} A^{1/2} V \]

We then can just put in the constants:

\[ \mu_{\text{sat}} = \frac{2L}{WC_{\text{ox}}} \left( \frac{d\sqrt{I_D}}{dV_G} \right)^2 \]

\[ \mu_{\text{sat}} = \frac{2 \times 50}{1000 \times 11 \times 10^{-9}} \times (4.79 \times 10^{-4})^2 \]

\[ \mu_{\text{sat}} = 2.09 \text{ cm}^2/\text{V}s \]

The other technique is to differentiate the data twice:

As with the square-root technique we require \( |V_D| \gg |V_G - V_T| \) for the saturation-regime approximation to be valid. We are told that \( V_G \approx 0 \), therefore we can extract values from the graph if \( V_D > V_G \). For saturation-regime we also require that the device is “on”. I have here chosen an average of values between \( 10V \leq V_G \leq 20V \):

\[ \frac{d^2I_D}{dV_G^2} = 6.05 \times 10^{-7} A^2/V^2 \]

We then can just put in the constants:

\[ \mu_{\text{sat}} = \frac{L}{WC_{\text{ox}}} \frac{d^2I_D}{dV_G^2} \]
\[
\mu_{sat} = \frac{50}{1000 \times 11 \times 10^{-9} \times 6.05 \times 10^{-7}}
\]

\[
\mu_{sat} = 2.75 \text{ cm}^2/\text{Vs}
\]

c) Using an approach of your choosing, estimate the threshold voltage of this transistor from the data provided. [6 marks]

There are two different ways of doing this. The first is the linear extrapolation method. Here we just plot the drain current as a function of gate voltage on a linear-linear scale:

We fit a straight line to this data. We must extrapolate away from \( V_T \), where the device exhibits subthreshold behavior. Here I fitted a straight line to the data where \( 25V \leq V_G \leq 45V \).

We identify the \( y \)-intercept as approximately \( V_G = 14V \). Using

\[
V_G = V_T + \frac{V_D}{2}
\]
\[ V_T = V_G - \frac{V_D}{2} \]

We know the applied drain voltage \( V_D = 10 \text{V} \), so the threshold voltage is:

\[ V_T = 14 - \frac{10}{2} = 9 \text{V} \]

The other approach is to consider transfer data in the saturation regime:

![Graph showing \( I_D^{1/2} \) vs. \( V_G \)]

Again we must extrapolate the data to \( I_D^{1/2} = 0 \). Because this approximation is only valid in the saturation regime, we can only consider data where: \(|V_D| \gg |V_G - V_T|\). Since \( V_D = 40 \text{V} \), we here fit to \( 20 \text{V} \leq V_G \leq 35 \text{V} \).

![Graph showing \( I_D^{1/2} \) vs. \( V_G \)]

In this case we just take the intercept as the threshold voltage directly:

\[ V_T = 7 \text{V} \]

**Question 2 [6 marks]:**
Figure 2 shows output characteristics of a field-effect transistor (FET), measured at applied drain voltages of $V_G = 30\, \text{V}$. This data is available to download here.

Figure 2 Output characteristics ($I_D$ vs $V_D$) of an example field-effect transistor. This data is available to download here.

a) From the data plotted in Figure 2, approximate the output conductance in the linear regime. Any reasonable valuable will be accepted assuming the technique is correct.[6 marks]

There are couple of ways to do this question – the first is to just to take the gradient of the output curve in the linear regime. What I do here is numerically differentiate the output curve and plot it as a function of drain voltage:

So we see that $g_d$ varies significantly as a function of drain voltage. Therefore we just take a value of $3\, \mu\text{S}$ as a representative value in this case.