University of the Philippines
Microelectronics and Microprocessors Laboratory

Lab Module 05 – Answer Sheet

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Class: SATURDAY AM
SCORE: XX/40

Instructions:

This is answer sheet is a format only. You may answer using any word processor (i.e. Microsoft Word, Libre Office, Latek, Google docs … etc.) but you need to submit either a pdf or docx file so we can comment on it. Make sure to put your name, student number, and indicate what lab class you are in. This is given in the format above. Name your file "coe197_class_lastname_studentnumber". For the class write "satam" or "satpm" if you're in the morning or afternoon class, respectively. For example: "coe197_satam_antonio_201101474".

When you make your document please maintain the order of the main sections (PART I, PART II, PART III, and PART IV) and stick to the numbering provided in this answer sheet. You may use this word document if you like.

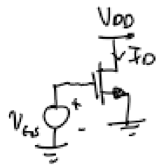
Answer with clear and concise solutions. Indicate your final answer (box it, bold it, change its color but please do not use red font color). For problems that require explanations, elaborate your thoughts. Any unclear answers will be marked wrong. There will be partial points.

Have fun and learn by heart!

Part I: Review

1. What are the small-signal parameters g_m, r_o, and $g_m r_o$? Mathematically, how do we get these? Use long-channel equations.

Consider the MOS



We know that

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

If we add a small voltage ΔV_{GS} to V_{GS}, such that $V_{GS} = V_{GS} + \Delta V_{GS}$, the new equation will be

$$I_D + \Delta I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}+\Delta V_{GS}-V_{TH})^2$$

$$= \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\left(1+\frac{\Delta V_{GS}}{V_{GS}-V_{TH}}\right)^2$$

We know that for a small ε, $(1+\varepsilon)^2 \approx 1+2\varepsilon$.

Thus, $I_D + \Delta I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\left(1+\frac{2\Delta V_{GS}}{V_{GS}-V_{TH}}\right)$

$$= \underbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2}_{I_D} + \underbrace{\mu_n C_{ox}\frac{W}{L}\left(\frac{\Delta V_{GS}}{V_{GS}-V_{TH}}\right)(V_{GS}-V_{TH})^2}_{\Delta I_D}$$

Looking at ΔI_D,

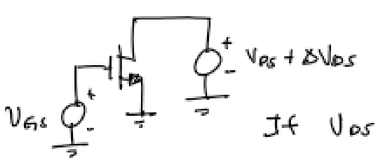
$$\Delta I_D = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})\Delta V_{GS}$$

Transconductance is defined as the small change in I_D from a small change in V_{GS}. (g_m)

$$\frac{\Delta I_D}{\Delta V_{GS}} = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH}) = \frac{2I_D}{V_{GS}-V_{TH}} = g_m = \sqrt{2kI_D}$$

where $k = \mu_n C_{ox}\frac{W}{L}$

Now consider the MOS.



In reality, V_{DS} affects the current I_D.

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

If $V_{DS} = V_{DS} + \Delta V_{DS}$, then

$$I_D + \Delta I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS}+\lambda\Delta V_{DS})$$

$$= \underbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})}_{I_D} + \underbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda\Delta V_{DS}}_{\Delta I_D}$$

$$\Delta I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda\Delta V_{DS} \rightarrow \frac{\Delta I_D}{\Delta V_{DS}} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda$$

We can model this with a resistor

$$r_o = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda} = \frac{1}{\lambda I_D} = r_o$$

$g_m r_o$ → intrinsic gain of a MOSFET (no external load)

$$\frac{V_{out}}{V_{in}} = -g_m r_o$$

Part II: Training

Question Q2.1:

Just to make sure you know how to read plots. What V_{GS} would give us $g_m \approx 250\ uS$? What about $g_m \approx 300\ uS$? What's g_m at 0.35 V?

Based on the plot, for $g_m = 250\mu S \rightarrow V_{GS} = 316mV$. For $g_m = 300\mu S \rightarrow V_{GS} = 344\ mV$
The value of g_m at $V_{GS} = 0.35V\ is \approx 310$ mS

Question Q2.2:

Complete the statements with increase, decrease, no change, or makes no sense and <u>be sure to indicate why</u>?

1. As W increases, g_m increases since g_m is directly proportional to W.
2. As L increases, g_m decreases since g_m is inversely proportional to L.
3. As W and L increases, g_m remains the same if both W and L are multiplied by the same factor.
4. As V_{GS} increases, g_m increases since I_D increases.

Bonus Question Q2.3:

Give an intelligent guess as to why the transconductance starts to decrease as we approach $V_{DS} = 1.2\ V$?

- As we approach $V_{DS} = 1.2V$, The transistor exits the saturation region.

Question Q2.4:

Roughly what is r_o for the entire saturation region?

- Approximately $120\ k\Omega$

Question Q2.5:

Complete the statements with increase, decrease, no change, or makes no sense and <u>be sure to indicate why</u>?

1. As W increases, r_o decreases since I_D increases.
2. As L increases, r_o increases since I_D decreases.
3. As W and L increases, r_o remains the same given that W and L are multiplied by the same factor.
4. As V_{DS} increases, r_o increases because of stronger channel length modulation.

Question Q2.6:

Fill the blanks with increase, decrease, or no change. When we increase the width, g_m increases and/but r_o decreases. When we increase the length, g_m decreases and/but r_o increases What kind of engineering problem do we have? Trade-off

Part III: Exercise

A. Reinforcement Learning

Let's make sure you understood this lab module.

1. How would you differentiate large-signal (DC) vs. small-signal (AC) analysis?
   - Large – signal analysis is used to compute the operating voltages of the transistor. In a sense, those operating voltages are where the small signals "sit".
2. How would you define transconductance g_m?
   - g_m is the small change in I_D due to a small change in V_{GS}.
   - How a small increase in gate voltage affects the drain current.
3. How would you define output impedance r_o?
   - It is the resistance seen by the load when looking at the output terminal of the transistor.
4. How would you define small-signal gain $g_m r_o$?
   - It is the gain when no load is connected to the output terminal.
5. Why is the input impedance infinite?
   - The input impedance is only infinite when DC is connected. The transistor has parasitic capacitances. Since capacitors block DC, the input impedance is infinite as far as DC signals are concerned.
6. What is the importance of the inductor in Figure 2.11?
   - Inductors act as short circuits at low frequencies. Since it has a high inductance, for non-DC signals, it acts as an open circuit. This way, we can find the gain better.
7. Why do we need to set AC = 1V for our AC analysis?
   - This is the voltage source used for the small signal model. In essence, we tell the circuit to use 1V AC for the small-signal computation.
8. In Figure 2.11, how is v_{out} indicative of $g_m r_o$? In other words, why is measuring v_{out} equal to $g_m r_o$?
   - $\frac{V_{out}}{V_{in}} = g_m r_o$. Since we set $V_{in} = 1V$, $V_{out} = g_m r_o$.
9. How would you define f_T?
   - f_T is defined as the frequency at which the short circuit current gain of the device drops to 1.
10. How do we increase f_T?
    - f_T is dominantly influenced by C_{GS}. To increase f_T, we can try to decrease C_{GS} as much as possible.
    - Increasing g_m also increases f_T

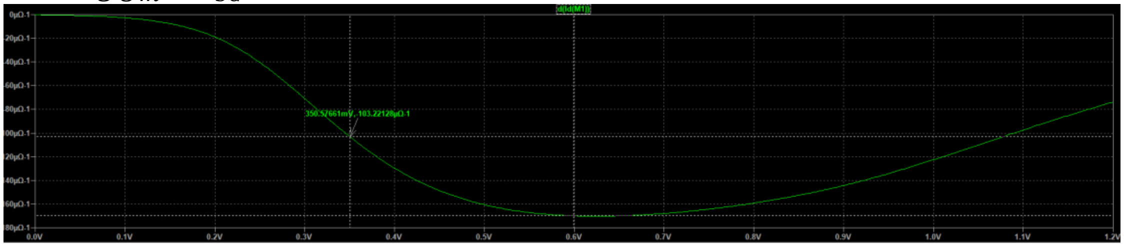
B. Current here, and current there!

Let's see if you know how to use the pre-made schematics for you. You are given the following schematics:

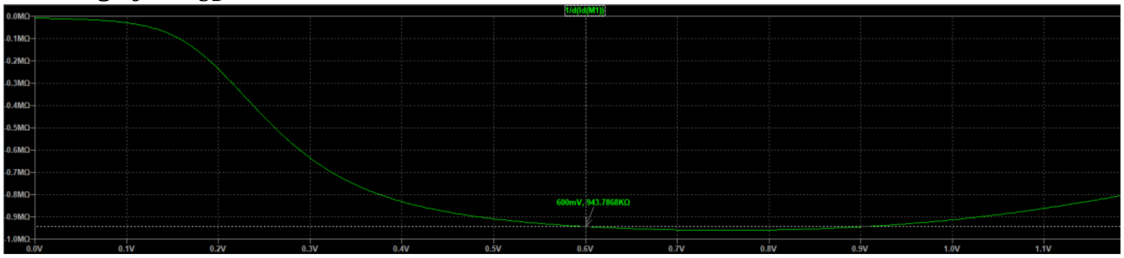
- "lab05_pmos_char"
- "lab05_pmos_gmro_extract"
- "lab05_pmos_ft_extract"

With $W = 10\ um$ and $L = $ 1um, Extract the following:

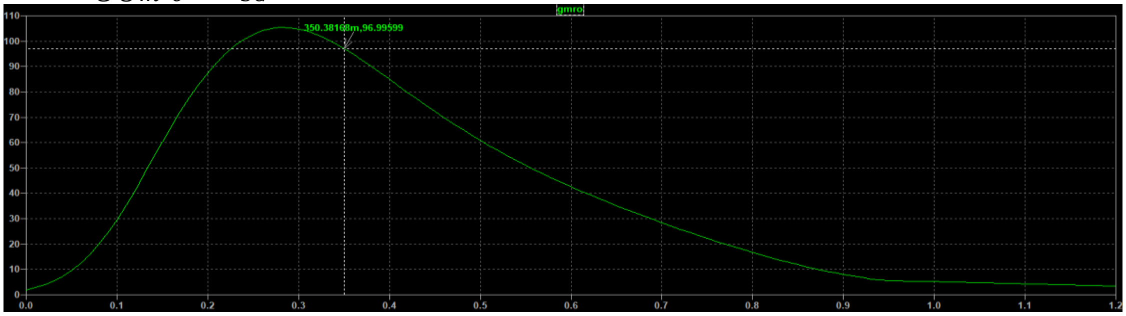
1. Reproduce the PMOS equivalent of Figure 2.8. Use $V_{SD} = 0.6\ V$. Show your plot and place a cursor showing g_m at $V_{SG} = 0.35\ V$.



2. Reproduce the PMOS equivalent of Figure 2.10. Use $V_{SG} = 0.35\ V$. Show your plot and place a cursor showing r_o at $V_{SD} = 0.6\ V$.



3. Reproduce the PMOS equivalent of Figure 2.15. Use $V_{SD} = 0.6\ V$. Show your plot and place a cursor showing $g_m r_o$ at $V_{SG} = 0.35\ V$.



4. Reproduce the PMOS equivalent of Figure 2.19. Use $V_{SD} = 0.6\ V$. Show your plot and place a cursor showing f_T at $V_{SG} = 0.35\ V$.