Analogue Electronics 1 (EE204FZ)

Tutorial 2 (Solutions)

Q1.

1. (C)
2. (A)
3. (B)
4. (B)
5. (D)

Q2.

1.

To use a MOSFET as a voltage controlled resistor, one needs to keep the device in the triode region. For an n-channel enhancement-type MOSFET, it means $V_{GS} > V_T$ and V_{DS} is relatively small ($V_{GS} - V_T > V_{DS}$). In the triode region, the drain current I_D is in a near-linear relation with the drain-source voltage, V_{DS}. The resistance of the device can be controlled by the gate-source voltage, V_{GS}. Resistors with very precise values in the range of 50 – 500 ohm can usually be realised.

MOSFET resistors are voltage controlled (their values can be changed after fabrication). They are also very precise and usually have much smaller footprints than other on-chip resistors.

2.

When the input to the inverter circuit is low (0 V), the PMOS is on and the NMOS is off. V_{out} is high (5 V). When the input to the inverter circuit is high (5 V), the PMOS is off and the NMOS is on. V_{out} is low (0 V). The output of the circuit is always the inversion of the input signal.

The current in the circuit is very little no matter whether the input signal is high or low. Since $P = IV$, the power consumption is also very small when the circuit is at either of its extremes. Power is only consumed when the output is being changed.

Q3.

The key is to work out the gate-source voltage V_{GS}. For an n-channel depletion-type MOSFET, if $V_{GS} > 0$, the device operates in the enhancement mode. If $V_{GS} < 0$, the device operates in the depletion mode. It is the opposite for a p-channel device.

(a) $V_G = 0$ and $V_S > 0$ (I_D goes from drain to source in an n-channel MOSFET). $V_{GS} = V_G - V_S < 0$. For an n-channel depletion-type MOSFET, it is in the depletion mode.

(b) $V_G = V_D > V_S$ and $V_{GS} > 0$. The n-channel MOSFET is in the enhancement mode.

(c) $V_G = 0$ and $V_S = 0$. The device works in neither the enhancement mode nor the depletion mode. One gets I_{DSS}.

(d) This is a p-channel depletion-type MOSFET. $V_G = 0$ and $V_S < 0$. Hence, $V_{GS} > 0$. It works in the depletion mode.

Q4.

The key to answer this question is to work out whether the MOSFET operates in the triode region or the saturation region. Students are also expected to understand how to correctly interpret the channel-length modulation parameter, λ. One complication is how to decide on the signs for various parameters for a PMOS device (different textbooks sometimes use different sign conventions). My own opinion is that students are free to use whatever sign convention they feel most comfortable with but the MOSFET equations they use have to be consistent with the sign convention they choose.

The MOSFET equations I choose to use are the following:

- $I_{\mathrm{D(tri)}} = \mu_{\mathrm{p}} C_{\mathrm{ox}} \frac{W}{L}[(V_{\mathrm{SG}} - |V_{\mathrm{T}}|)V_{\mathrm{SD}} - \frac{V_{\mathrm{SD}}^2}{2}]$ (in the triode region)
- $I_{\mathrm{D(sat)}} = \frac{1}{2}\mu_{\mathrm{p}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{SG}} - |V_{\mathrm{T}}|)^2(1 + |\lambda| V_{\mathrm{SD}})$ (in the saturation region)

The convention used here keeps all the variables in the equations positive. As discussed above, there are other ways of writing these equations depending on how signs are being assigned to the variables. All these ways should be deemed correct as long as the equations are consistent with the sign convention that is chosen. Most importantly, the equations used should correctly represent the underlying physics, e.g., the channel-length modulation parameter increases the magnitude of the drain current in the saturation region.

V_G = 0 V, V_S = 5 V, so $V_{SG} = V_S - V_G$ = 5 V. This is the same for all four cases.

(a) V_D = +4 V and $V_{SD} = V_S - V_D$ = 5 V – 4 V = 1 V.

$V_{SG} - |V_T|$ = 5 V – 1.5 V = 3.5 V > V_{SD} = 1 V. The device is in the triode region.

$$I_{\mathrm{D(tri)}} = \left(80 \times 10^{-6}\frac{\mathrm{A}}{\mathrm{V}^2}\right)\left[(3.5\ \mathrm{V})(1\ \mathrm{V}) - \frac{(1\ \mathrm{V})^2}{2}\right] = 2.40 \times 10^{-4}\ \mathrm{A} = 240\ \mu\mathrm{A}$$

(Some students may include the channel-length modulation parameter into the above equation. In this case, one will obtain a drain current of 245 µA. I would also count it as being correct. This point is discussed differently in different textbooks. Although I have a personal opinion on which version is "more" correct, I don't want to get into this rather "messy" debate and try to force my opinion onto the class).

(b) V_D = +1.5 V and $V_{SD} = V_S - V_D$ = 5 V – 1.5 V = 3.5 V.

$V_{SG} - |V_T|$ = 5 V – 1.5 V = 3.5 V = V_{SD}. Pinch-off sets in.

$$I_{\mathrm{D(sat)}} = \frac{1}{2}\left(80 \times 10^{-6}\frac{\mathrm{A}}{\mathrm{V}^2}\right)(3.5\ \mathrm{V})^2[1 + (0.02)(3.5\ \mathrm{V})] = 5.24 \times 10^{-4}\ \mathrm{A} = 524\ \mu\mathrm{A}$$

(c) V_D = 0 V and $V_{SD} = V_S - V_D$ = 5 V – 0 V = 5 V.

$V_{SG} - |V_T|$ = 5 V – 1.5 V = 3.5 V < V_{SD} = 5 V. The device is in the saturation region.

$$I_{\mathrm{D(sat)}} = \frac{1}{2}\left(80 \times 10^{-6}\frac{\mathrm{A}}{\mathrm{V}^2}\right)(3.5\ \mathrm{V})^2[1 + (0.02)(5\ \mathrm{V})] = 5.39 \times 10^{-4}\ \mathrm{A} = 539\ \mu\mathrm{A}$$

(d) V_D = -5 V and $V_{SD} = V_S - V_D$ = 5 V – (-5 V) = 10 V.

$V_{SG} - |V_T|$ = 5 V – 1.5 V = 3.5 V < V_{SD} = 10 V. The device is in the saturation region.

$$I_{\mathrm{D(sat)}} = \frac{1}{2}\left(80 \times 10^{-6}\frac{\mathrm{A}}{\mathrm{V}^2}\right)(3.5\ \mathrm{V})^2[1 + (0.02)(10\ \mathrm{V})] = 5.88 \times 10^{-4}\ \mathrm{A} = 588\ \mu\mathrm{A}$$

Q5.

The n-channel enhancement-type MOSFET operates in the saturation region. To see this, we first identify that $V_G = V_D$ and $V_{GS} = V_{DS}$ since no current goes into the gate terminal. $V_S = 0$ (the source terminal is grounded). Thus, $V_{GS} - V_T = V_{DS} - V_T < V_{DS}$. The MOSFET is in the saturation region.

In order to solve the question (without using the graphic method), we apply Kirchhoff's voltage law:

$$V_{\mathrm{D}} = V_{\mathrm{DD}} - I_{\mathrm{D(sat)}}R = V_{\mathrm{DD}} - \frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}(\frac{W}{L})(V_{\mathrm{GS}} - V_{\mathrm{T}})^2 R$$

We can replace V_{GS} by $V_{DS} = V_D$ (since $V_S = 0$) and it leads to a quadratic equation about V_D:

$$V_{\mathrm{D}} = V_{\mathrm{DD}} - \frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}(\frac{W}{L})(V_{\mathrm{D}} - V_{\mathrm{T}})^2 R$$

Insert all the parameters from the question:

$$V_{\mathrm{D}} = (5\ \mathrm{V}) - \frac{1}{2}(250 \times 10^{-6}\,\frac{\mathrm{A}}{\mathrm{V}^2})(100\ \mathrm{ohm})(V_{\mathrm{D}} - 0.5\ \mathrm{V})^2$$

Solving the quadratic equation gives:

$$V_{\mathrm{D}} = 4.77\ \mathrm{V} \text{ and } I_{\mathrm{D(sat)}} = \frac{V_{\mathrm{DD}} - V_{\mathrm{D}}}{R} = \frac{5\ \mathrm{V} - (4.77\ \mathrm{V})}{100\ \mathrm{ohm}} = 230\ \mathrm{mA}$$