4.7. Consider an n-channel MOSFET with $t_{ox} = 20$ nm, $\mu_n = 650$ cm$^2$/V · s, $V_t = 0.8$ V, and $W/L = 10$. Find the drain current in the following cases:

(a) $v_{GS} = 5$ V and $v_{DS} = 1$ V.
(b) $v_{GS} = 2$ V and $v_{DS} = 1.2$ V.
(c) $v_{GS} = 5$ V and $v_{DS} = 0.2$ V.
(d) $V_{GS} = v_{DS} = 5$ V.

First find

$$k'_n \frac{W}{L} = \mu_n \frac{t_{ox} W}{\varepsilon_{ox} L}$$

$$= 650 \times (10^{-2})^2 \times 3.45 \times 10^{-11} \times \frac{20 \times 10^{-9}}{10} \times 10$$

$$= 1.12 \text{ mA/V}^2$$

(a) The circuit is operating in triode mode,

$$i_D = k'_n \frac{W}{L} \left[ (v_{GS} - V_t) v_{DS} - \frac{v_{DS}^2}{2} \right]$$

$$= 1.12 \times \left[ (5 - 0.8) \times 1 - \frac{1}{2} \right]$$

$$= 4.14 \text{ mA}$$

(b) The circuit is operating in triode mode,

$$i_D = k'_n \frac{W}{L} \left[ (v_{GS} - V_t) v_{DS} - \frac{v_{DS}^2}{2} \right]$$

$$= 1.12 \times \left[ (2 - 0.8) \times 1.2 - \frac{1.2^2}{2} \right]$$

$$= 0.81 \text{ mA}$$

(c) The circuit is operating in triode mode,

$$i_D = k'_n \frac{W}{L} \left[ (v_{GS} - V_t) v_{DS} - \frac{v_{DS}^2}{2} \right]$$

$$= 1.12 \times \left[ (5 - 0.2) \times 0.2 - \frac{0.2^2}{2} \right]$$

$$= 1.05 \text{ mA}$$
(d) The circuit is operating in saturation mode,

\[ i_D = \frac{k'_n W}{2L} (v_{GS} - V_t)^2 \]

\[ = \frac{1.12}{2} (5 - 0.8)^2 \]

= 9.9 mA

4.17. An NMOS transistor, fabricated with \( W = 100 \mu m \) and \( L = 5 \mu m \) in a technology for which \( k'_n = 50 \mu A/V^2 \) and \( V_t = 1 V \), is to be operated at very low values of \( v_{DS} \) as a linear resistor. For \( v_{GS} \) varying from 1.1 V to 11 V, what range of resistor values can be obtained? What is the available range if

(a) the device width is halved?
(b) the device length is halved?
(c) both the width and the length are halved?

Since we will be looking at very small values of \( v_{DS} \) we ignore the second term in the triode mode expression and are left with

\[ i_D = k'_n \frac{W}{L} (v_{GS} - V_t) v_{DS} \]

The resistance is then

\[ R = \frac{1}{k'_n \frac{W}{L} (v_{GS} - V_t)} \]

(larger values of \( v_{GS} \) result in smaller resistances). For \( v_{GS} = 1.1 V \) we get

\[ R_{max} = \frac{1}{50 \times 10^{-6} \times \frac{100}{5} \times (1.1 - 1)} = 10 k\Omega \]

For \( v_{GS} = 11 V \) we get

\[ R_{min} = \frac{1}{50 \times 10^{-6} \times \frac{100}{5} \times (11 - 1)} = 100 \Omega \]

4.36. The PMOS transistor in the circuit of Fig. P4.36 has \( V_t = -0.7 V \), \( \mu_p C_{ox} = 60 \mu A/V^2 \), \( L = 0.8 \mu m \), and \( \lambda = 0 \). Find the values required for \( W \) and \( R \) in order to establish a drain current of 115 \( \mu A \) and a voltage \( V_D = 3.5 V \).
To find the value of $R$ we use

$$V_D = R I_D$$

$$R = \frac{V_D}{I_D} = \frac{3.5}{115 \times 10^{-6}} = 30.4 \, \text{k}\Omega$$

To find $W$ we use, for saturation mode,

$$i_D = \frac{\mu_n C_{ox} W}{2} \left( v_{SG} + V_t \right)$$

$$W = \frac{2i_D L}{\mu_c C_{ox} (v_{SG} + V_t)} = \frac{2 \times 115 \times 10^{-6} \times 0.8 \times 10^{-6}}{60 \times 10^{-6} (1.5 - 0.7)} = 3.8 \, \mu\text{m}$$

4.37. The NMOS transistors in the circuit of Fig. P4.37 have $V_t = 1 \, \text{V}$, $\mu_n C_{ox} = 120 \, \mu\text{A}/\text{V}^2$, $\lambda = 0$, and $L_1 = L_2 = 1 \, \mu\text{m}$. Find the required values of gate width for each of $Q_1$ and $Q_2$, and the value of $R$ to obtain the voltage and current values indicated.
The two MOSFETS are operating in saturation mode and we know $V_{DS}$. The value of $R$ is found from

$$V_{DD} - V_{D2} = I_D R$$

$$R = \frac{V_{DD} - V_{D2}}{I_D} = \frac{5 - 3.5}{120 \times 10^{-6}} = 12.5 \text{ k}\Omega$$

For $Q_2$ we have $V_{GS2} = V_{D2} - V_{D1} = 2$ V, and

$$i_D = \frac{\mu_n C_{ox} W_2}{2 L_2} (V_{GS2} - V_t)^2$$

$$W_2 = \frac{2 L_2 i_D}{\mu_n C_{ox} (V_{GS2} - V_t)^2}$$

$$= \frac{2 \times 1 \times 10^{-6} \times 120 \times 10^{-6}}{120 \times 10^{-6} (2 - 1)^2}$$

$$= 2 \mu\text{m}$$

For $Q_1$ we have $V_{GS1} = V_{D1} = 1.5$ V, and

$$W_1 = \frac{2 L_1 i_D}{\mu_n C_{ox} (V_{GS1} - V_t)^2}$$

$$= \frac{2 \times 1 \times 10^{-6} \times 120 \times 10^{-6}}{120 \times 10^{-6} (1.5 - 1)^2}$$

$$= 8 \mu\text{m}$$