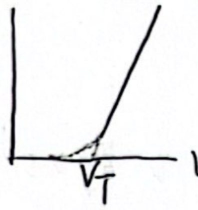
Problem Set 8 Solution

1. (15 points) (a) When a reversed-biased source-to-substrate voltage is applied, the depletion region of source-substrate region junction widens, so more gate voltage should be applied to invert the channel. (5')

(b) Subthreshold conduction refers to the phenomenon where the drain current (I_D) exists even when input voltage is less than or equal to the threshold voltage ($V_{GS} \le V_t$) (3')

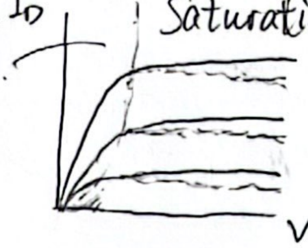
Plot:



(2')

(c) Channel length modulation means when the MOSFET is biased in the saturation region, the effective channel length is not a constant but depends on drain-to-source voltage. (3')

I-V curve:



"—" Solid line: with channel length modulation
"- - -" dashed line: without ~.

(2')

2. (20 points) 5'+5'+5'+5'

(a) $|V_{DS}| = 0.25V$ $|V_{GS}-V_T| = 0.4V$ Since $|V_{DS}| < |V_{GS}-V_T|$, in linear mode (2')

$I_D = k_p' \cdot \frac{W}{L}(|V_{GS}-V_T| - \frac{1}{2}|V_{DS}|)|V_{DS}| = 0.1 \times 15 \times (0.4 - \frac{1}{2}\times 0.25) \times 0.25 \simeq \boxed{0.103mA}$ (3')

(b) $|V_{DS}| = 1V$. $|V_{GS}-V_T| = 0.4V$. Since $|V_{DS}| > |V_{GS}-V_T|$ in saturation mode (2')

$I_D = \frac{1}{2}k_p' \cdot \frac{W}{L}(|V_{GS}-V_T|)^2 = \frac{1}{2}\times 0.1 \times 15 \times 0.4^2 = \boxed{0.12mA}$ (3')

(c) $|V_{DS}| = 1V$. $|V_{GS}-V_T| = 0.8V$. Since $|V_{DS}| > |V_{GS}-V_T|$, in saturation mode. (2')

$I_D = \frac{1}{2}k_p' \cdot \frac{W}{L} \cdot (|V_{GS}-V_T|)^2 = \frac{1}{2}\times 0.1 \times 15 \times 0.8^2 = \boxed{0.48mA}$ (3')

(d) $|V_{DS}| = 2V$. $|V_{GS}-V_T| = 0.8V$. $|V_{DS}| > |V_{GS}-V_T|$ in sat mode (2') $I_D = \boxed{0.48mA}$ (3')

3. (15 points) 5'+5'+5'

(a) When $V_{GS} = 0V$, $V_{GS} < V_T$, $I_D = 0$.

when $V_{GS} = 0.6V$, $V_{DS(sat)} = V_{GS} - V_T = \boxed{0.15V}$ $I_{D(sat)} = \mu_n C_{ox} \frac{W}{2L} V_{DS,sat}^2$

$= 425 \times \frac{3.9 \times 8.85 \times 10^{-14}}{11 \times 10^{-7}} \times \frac{20}{2 \times 1.2} \times 0.15^2 \simeq \boxed{0.025mA}$

When $V_{GS} = 1.2V$, $V_{DS(sat)} = V_{GS} - V_T = \boxed{0.75V}$ $I_{D(sat)} = \mu_n C_{ox} \frac{W}{2L} V_{DS,sat}^2 \simeq \boxed{0.625mA}$

When $V_{GS} = 1.8V$, $V_{DS(sat)} = V_{GS} - V_T = \boxed{1.35V}$ $I_{D(sat)} \simeq \boxed{2.025mA}$

When $V_{GS} = 2.4V$, $V_{DS(sat)} = V_{GS} - V_T = \boxed{1.95V}$ $I_{D(sat)} \simeq \boxed{4.226mA}$ (2')

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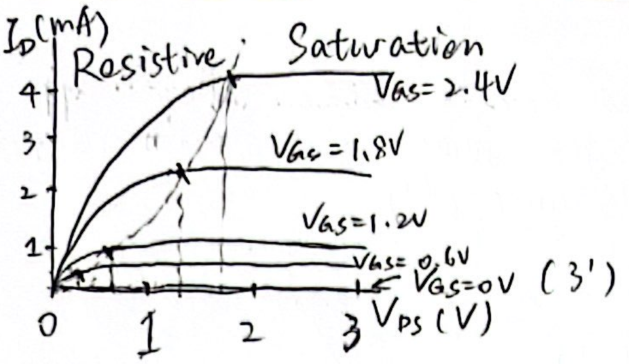
Plot:

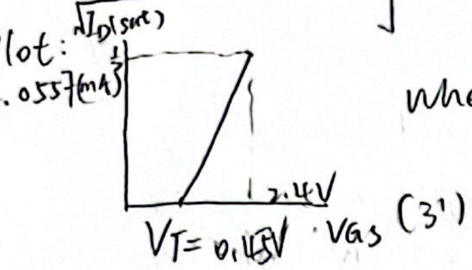


(3')

(b) $\sqrt{I_{D(sat)}} = \sqrt{\frac{W\mu_n C_{ox}}{2L}}\,(V_{GS}-V_T).$

slope $= \sqrt{\frac{\mu C_{ox} W}{2L}} = \sqrt{\frac{425\times\frac{3.9\times8.85\times10^{-14}}{11\times10^{-7}}\times20}{2\times1.2}} = 0.0333\ (F/V\cdot s)^{\frac{1}{2}}$ (1')

Plot:



(3')

when $V_{GS}=2.4V$. $\sqrt{I_{D(sat)}} \simeq 2.0557(mA)^{\frac{1}{2}}$ (1')

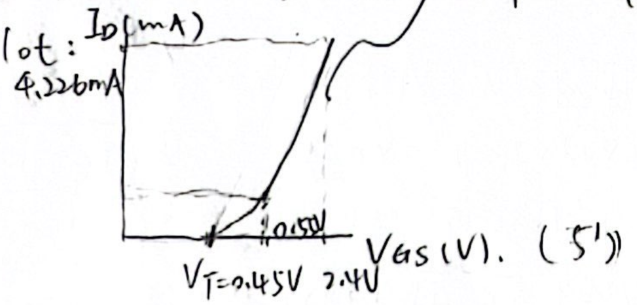
(c) when $0<V_{GS}\le V_T=0.45V$, $I_D=0A$

when $V_T<V_{GS}\le V_{DS}+V_T$, saturation region

and when $V_{GS}\ge V_{DS}+V_T$ linear region

$I_D=\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)$. slope $= 425\times\frac{3.9\times8.85\times10^{-14}}{11\times10^{-7}}\times\frac{20}{1.2} = 2.223\times10^{-3}S$

Plot:



(5')

4. (5 points)

$\phi_{fp}=\frac{kT}{q}\ln\frac{N_a}{n_i}=0.0259\times\ln\frac{10^{16}}{1.5\times10^{10}}\simeq0.347V$ (1')

$\Delta V_T=V_T'-V_T=\gamma\left[\sqrt{2\phi_{fp}+V_{SB}}-\sqrt{2\phi_{fp}}\right]$

$0.5-V_T=0.12\times\left(\sqrt{0.347\times2+2.5}-\sqrt{0.347\times2}\right)$ (2')

$\Rightarrow V_T\simeq\boxed{0.386V}$ (2')

5. (20 points) 5'+5'+5'+5'

(a) $\phi_{fp}=\frac{kT}{q}\ln\frac{N_a}{n_i}=0.0259\times\ln\frac{2\times10^{16}}{1.5\times10^{10}}\simeq0.365V$

$V_{DS(sat)}=V_{GS}-V_T=1-0.4=0.6V$ (2')

$$\Delta L = \sqrt{\frac{2\varepsilon_s}{eN_a}}\left[\sqrt{\phi_{fp}+V_{DS}} - \sqrt{\phi_{fp}+V_{DS(sat)}}\right] = \sqrt{\frac{2\times 11.7\times 8.85\times 10^{-14}}{1.6\times 10^{-19}\times 2\times 10^{16}}}\times\left[\sqrt{0.365+2}-\sqrt{0.365+0.6}\right]$$

$\simeq \boxed{1.413\times 10^{-5}\ cm}$ (3')

(b) $V_{DS(sat)} = V_{GS}-V_T = 1-0.4 = 0.6V$. (2') $\Delta L = 2.544\times 10^{-5}\times(\sqrt{0.365+4}-\sqrt{0.365+0.6})$

$\simeq \boxed{2.816\times 10^{-5}\ cm}$ (3')

(c) $V_{DS(sat)} = V_{GS}-V_T = 2-0.4 = 1.6V$. (2') $\Delta L = 2.544\times 10^{-5}\times(\sqrt{0.365+2}-\sqrt{0.365+1.6}) \simeq \boxed{3.462\times 10^{-6}\ cm}$ (3')

(d) $V_{DS(sat)} = 1.6V$ (2') $\Delta L = 2.544\times 10^{-5}\times(\sqrt{0.365+4}-\sqrt{0.365+1.6}) \simeq \boxed{1.749\times 10^{-5}\ cm}$ (3')

6. (10 points)

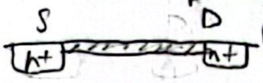
Since $V_{DS(sat)} = V_{GS}-V_T$. $V_{GS} = V_{DS(sat)}+V_T = 5V+1V = \boxed{6V}$ (1')

When $V_{DS}=10V > V_{DS(sat)}$. in saturation mode. $\boxed{g_D = \frac{dI_{DS}}{dV_{DS}} = 0}$ (3')

$g_{m(sat)} = \frac{dI_{DS}}{dV_{GS}} = \frac{W}{L}\mu_n C_{ox}(V_{GS}-V_T) = k_n(V_{GS}-V_T)$

Since $I_{D(sat)} = \frac{k_n}{2}(V_{GS}-V_T)^2 \Rightarrow 0.1mA = \frac{k_n}{2}\times(5V)^2 \Rightarrow k_n = 8\times 10^{-6}\ A/V^2$

$g_{m(sat)} = 8\times 10^{-6}\times 5 = \boxed{4\times 10^{-5}\ S}$ (3')

For $V_{DS}=1V$. 

(1') For $V_{DS}=5V$ 

(1')

For $V_{DS}=10V$. 

(1')

7. (15 points) 5'+5'+5'

(a) $\frac{I_D'}{I_D} = \frac{I_s e^{V_{GS}'/nV_t}}{I_s e^{V_{GS}/nV_t}} = e^{(V_{GS}'-V_{GS})/nV_t}$ $\quad V_{GS}'-V_{GS} = nV_t \ln\frac{I_D'}{I_D}$

for $n=1$. $V_{GS}'-V_{GS} = 0.0259\times\ln 10 \simeq \boxed{0.0596V}$ (5')

(b) for $n=1.5$. $V_{GS}'-V_{GS} = 1.5\times 0.0259\times\ln 10 \simeq \boxed{0.0895V}$ (5')

(c) for $n=2.1$, $V_{GS}'-V_{GS} = 2.1\times 0.0259\times\ln 10 \simeq \boxed{0.125V}$ (5')

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