Exercise 1

As is pentavalent impurity

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As is pentavalent impurity $\Rightarrow$ n-type

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$$n_n = N_D = 10^{25} \text{ carrier/m}^3$$

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(1) $n_n p_n = n_i^2$

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(1) $\underline{n_n} P_n = n_i^2$

$\checkmark$

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$$n_n = N_D = 10^{25} \text{ carrier}/m^3$$

(1) $\underbrace{n_n}_{\checkmark} \underbrace{p_n}_{?} = n_i^2$

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As is pentavalent impurity $\Rightarrow$ n-type

$$n_n = N_D = 10^{25} \text{ Carrier}/m^3$$

(1) $\underset{\checkmark}{\underline{n_n}}\ \underset{?}{\underline{p_n}} = \underset{?}{\underline{n_i^2}}$

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As is pentavalent impurity $\Rightarrow$ n-type

$n_n = N_D = 10^{25}$ carrier/m^3

(1) $\underset{\checkmark}{\underline{n_n}}\ \underset{?}{\underline{p_n}} = \underset{?}{\underline{n_i^2}}$

$n_i = 1.1 \times 10^{16}$ carriers/m^3 @ room temprature (300 K)

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$n_n = N_D = 10^{25}$ carrier/m^3

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$\checkmark \quad ? \quad ?$

$n_i = 1.1 \times 10^{16}$ carriers/m^3 @ room temprature (300 K)

number of carriers doubled every 11°C (see: p.1 k. martin)

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As is pentavalent impurity $\Rightarrow$ n-type

$$n_n = N_D = 10^{25} \text{ carrier}/m^3$$

(1) $$\underbrace{n_n}_{\checkmark} \underbrace{P_n}_{?} = \underbrace{n_i^2}_{?}$$

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number of carriers doubled every 11°C (see: P.1 K. martin)

$n_i = 4.4 \times 10^{16}$ carrier/m^3 @ (322 K)

(1) $$P_n = \frac{n_i^2}{N_D} = \frac{(4.4 \times 10^{16})^2}{10^{25}}$$

Exercise 1

As is pentavalent impurity $\Rightarrow$ n-type

$n_n = N_D = 10^{25}$ carrier/m^3

(1) $\underbrace{n_n}_{\checkmark} \underbrace{P_n}_{?} = \underbrace{n_i^2}_{?}$

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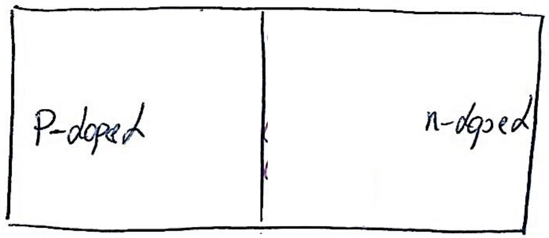
$n_i = 4.4 \times 10^{16}$ carrier/m^3 @ (322 K)

(1) $P_n = \dfrac{n_i^2}{N_D} = \dfrac{(4.4 \times 10^{16})^2}{10^{25}} = 1.9 \times 10^8$ carriers/m^3

Exercise 2: What is built-in Voltage?



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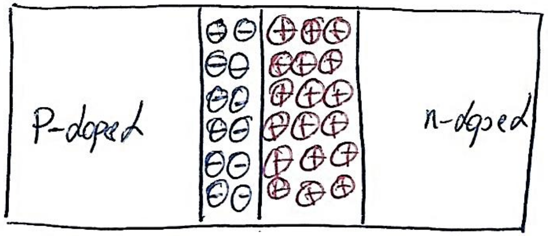

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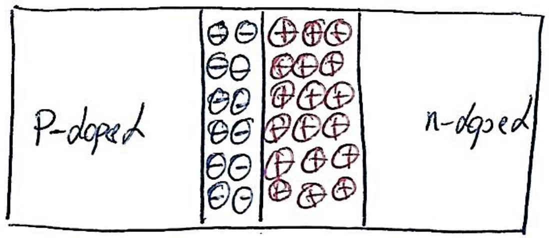

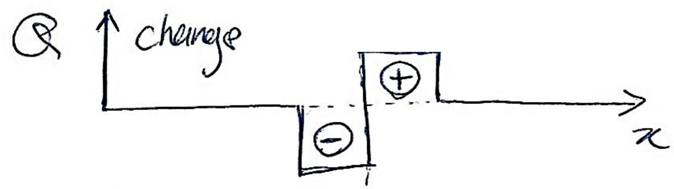

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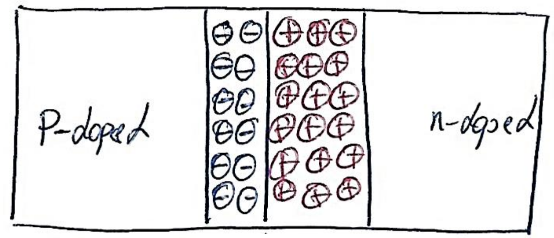
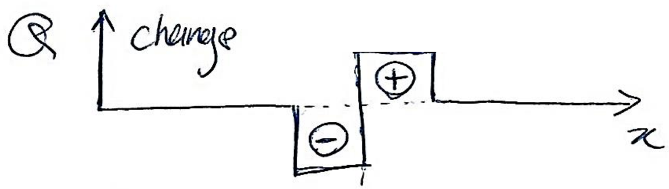
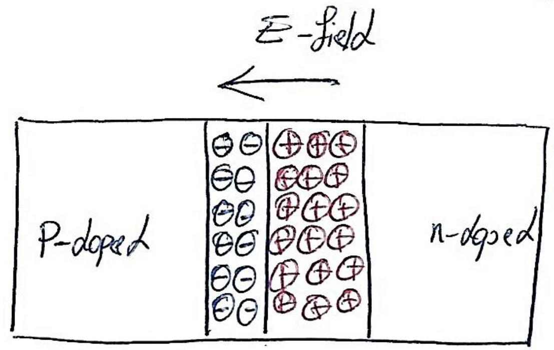
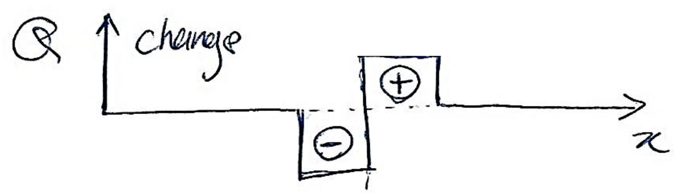




$$\nabla \cdot E = \rho / \varepsilon$$

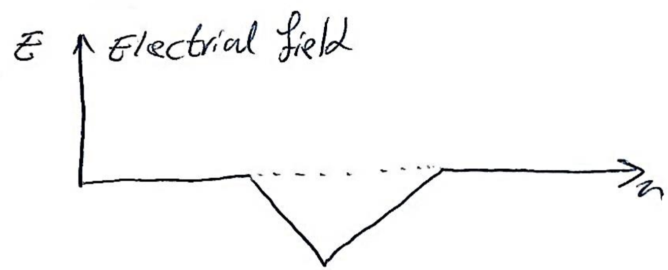
Exercise 2: What is built-in Voltage?





$$\nabla \cdot E = \rho / \varepsilon$$

Gaus's law



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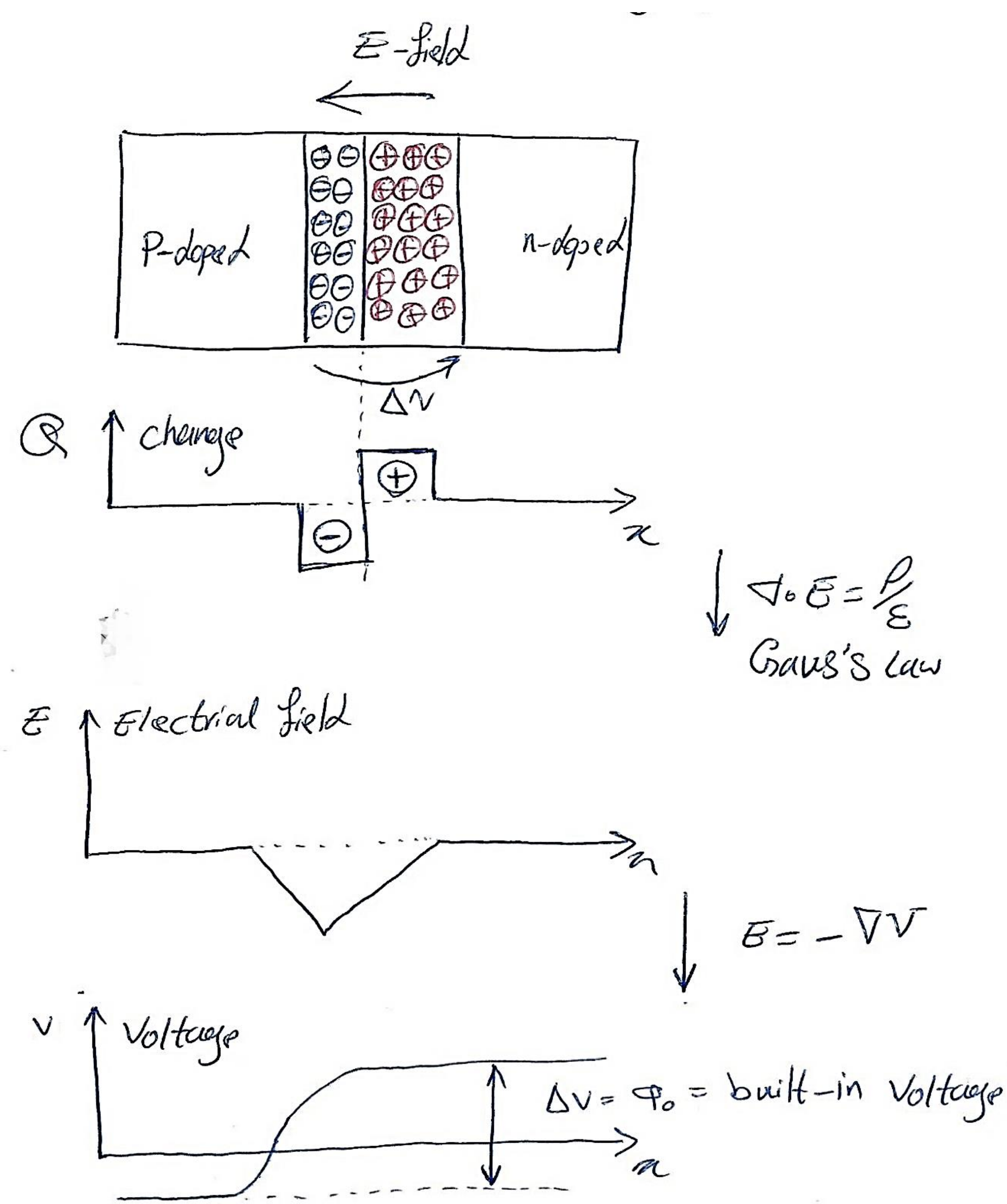

Exercise 2

junction built-in voltage:

$$\varphi_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

V_T: @ 300°K ⇒ 26 mV

n_i: @ 300°K = 1.1×10^{16} Carries/m^3

Exercise 2

junction built-in voltage :

$$\varphi_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \times \ln\left(\frac{10^{25} \times 10^{22}}{(1.1 \times 10^{16})^2}\right) = 0.89\ V$$

@ 300°K ⇒ 26 mV

@ 300°K = 1.1×10^{16} Carriers/m^3

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@ $300^\circ K \Rightarrow 26\ mV$

@ $300^\circ K = 1.1 \times 10^{16}$ Carries/m^3

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one Side heavily dopped.

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$T \uparrow \longrightarrow \varphi_0 ?$

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$T \uparrow \longrightarrow n_i \uparrow$

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Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one side heavily dopped.

$T\uparrow \longrightarrow \varphi_0$?

$T\uparrow \longrightarrow n_i \nearrow$

$T\uparrow \longrightarrow V_T \nearrow$, $V_T = \frac{kT}{q} = 26,8$ mV

Exercise 2

junction built-in voltage:

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@ 300°K ⇒ 26 mV

@ 300°K = 1.1×10^{16} Carries/m^3

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one side heavily dopped.

$T \uparrow \longrightarrow \varphi_0$?

$T \uparrow \longrightarrow n_i \uparrow$

$T \uparrow \longrightarrow V_T \uparrow$, $V_T = \frac{kT}{q} = 26,8\ mV$

$$\varphi_0 = V_T \ln \frac{10}{(2 \times 1.1 \times 10^{16})^2}$$

Exercise 2

junction built-in voltage:

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V_T @ $300^\circ K \Rightarrow 26\ mV$

n_i @ $300^\circ K = 1.1 \times 10^{16}$ Carries/m^3

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one Side heavily dopped.

$T\uparrow \longrightarrow \varphi_0$?

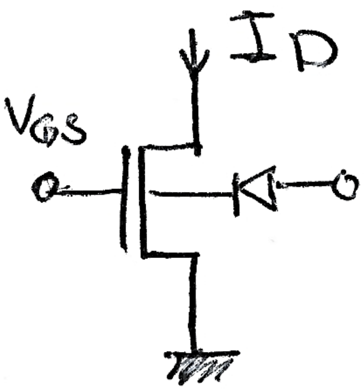
$T\uparrow \longrightarrow n_i \nearrow$

$T\uparrow \longrightarrow V_T \nearrow$, $V_T = \frac{kT}{q} = 26,8\ mV$

$$\varphi_0 = V_T \ln \frac{10}{(2 \times 1.1 \times 10^{16})^2} = 0.88\ V$$

φ_0 decreases

Exercise 4

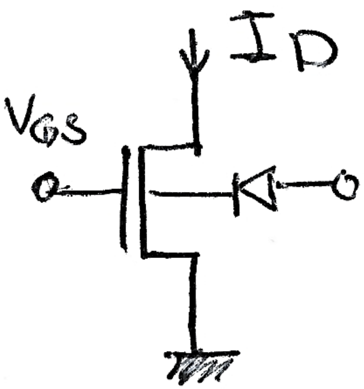


n-channel transistor

$N_D = 10^{25}$ atoms/m^3

$N_A = 10^{22}$ atom/m^3

Exercise 4



n-channel transistor

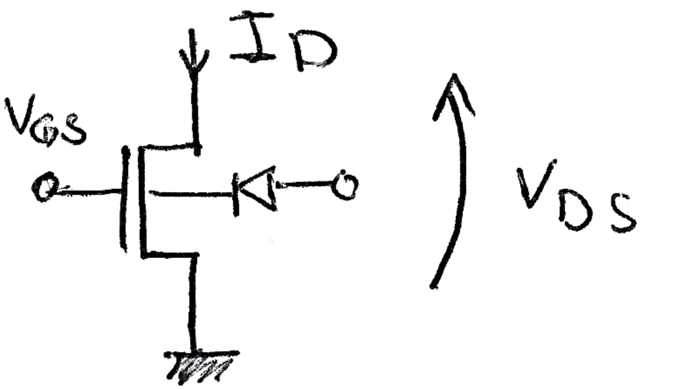
$N_D = 10^{25}$ atoms/m^3

$N_A = 10^{22}$ atom/m^3

$W = 50\,\mu m$

$L = 1.5\,\mu m$

Exercise 4



n-channel transistor

$N_D = 10^{25}$ atoms/m^3

$N_A = 10^{22}$ atom/m^3

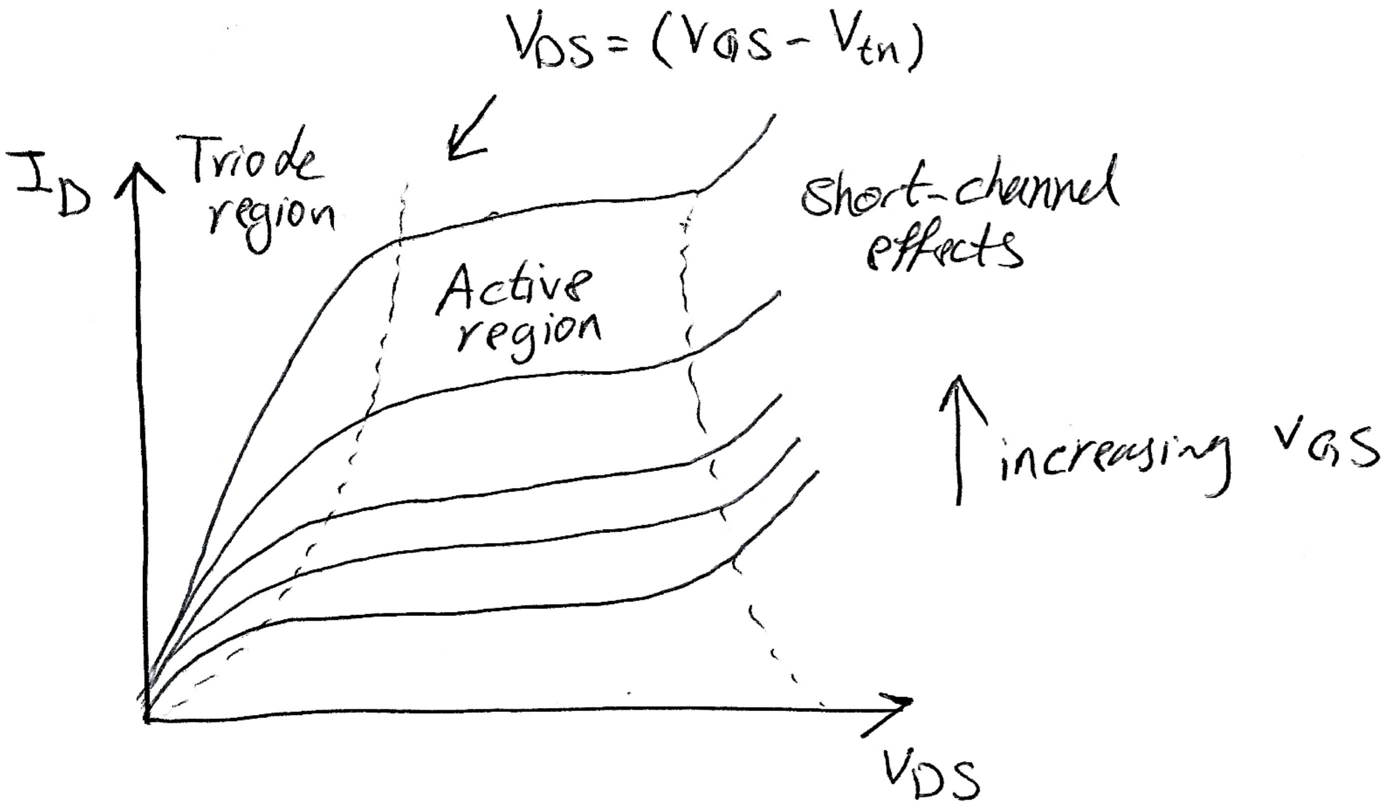
$W = 50\,\mu m$

$L = 1.5\,\mu m$

$V_{GS} = 1.1\,V$

$V_{DS} = V_{eff}$

Exercise 4: determine operational mode



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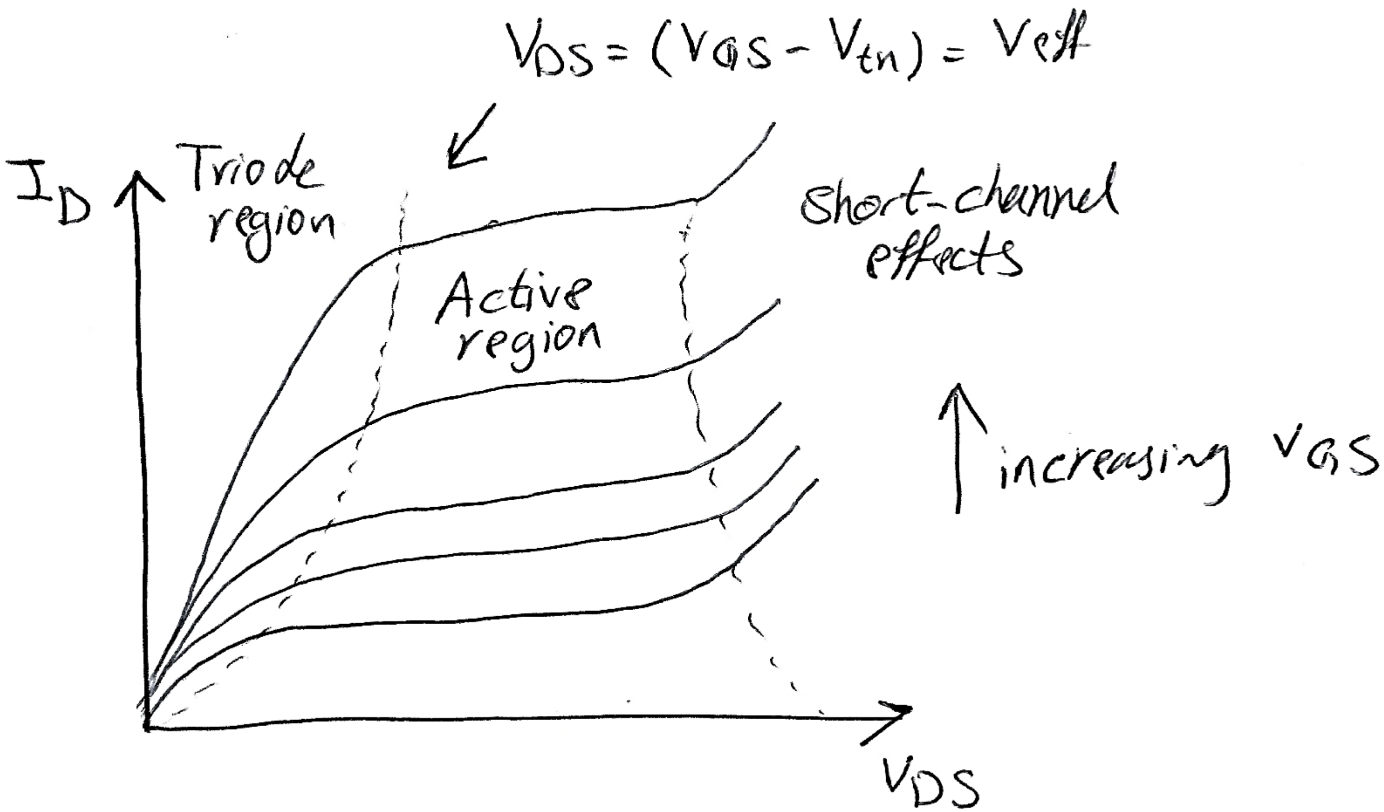

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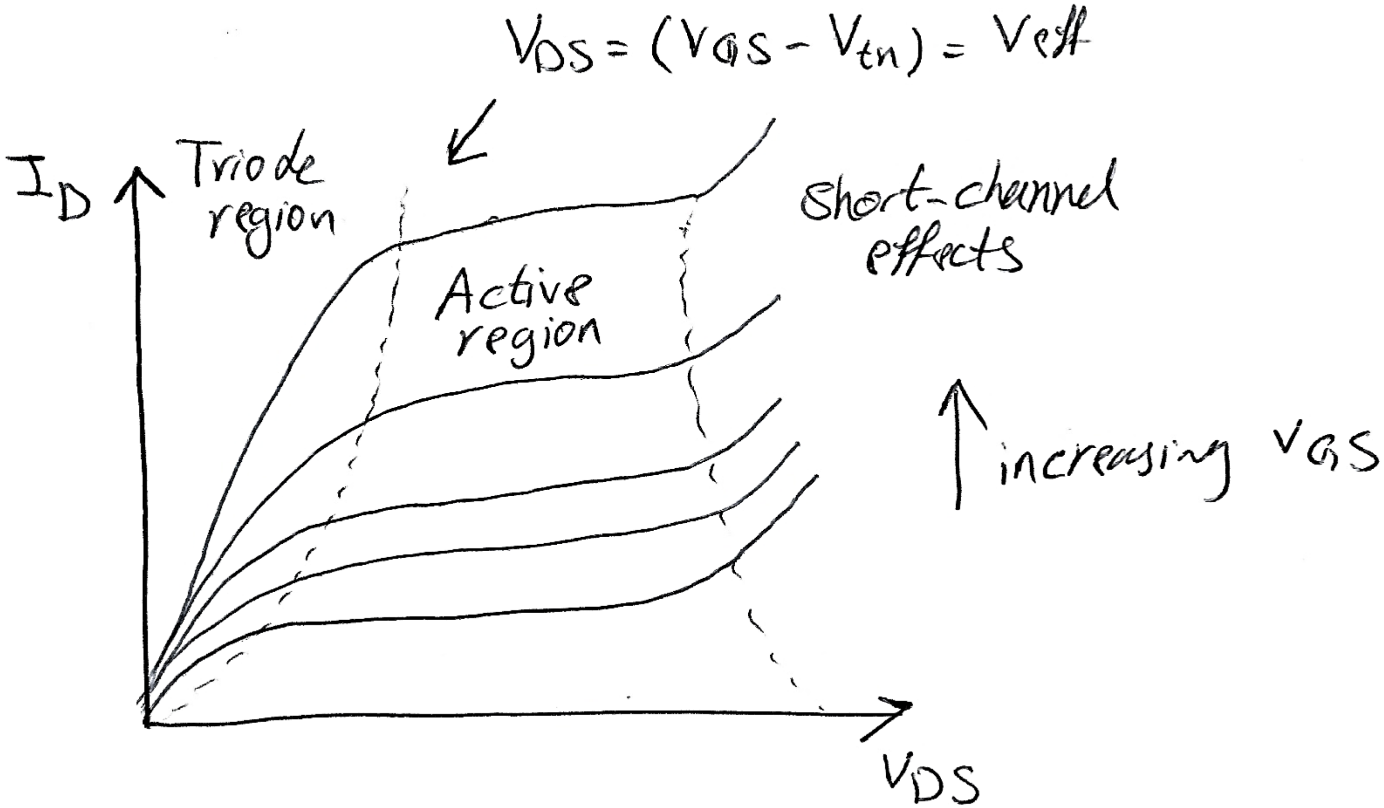
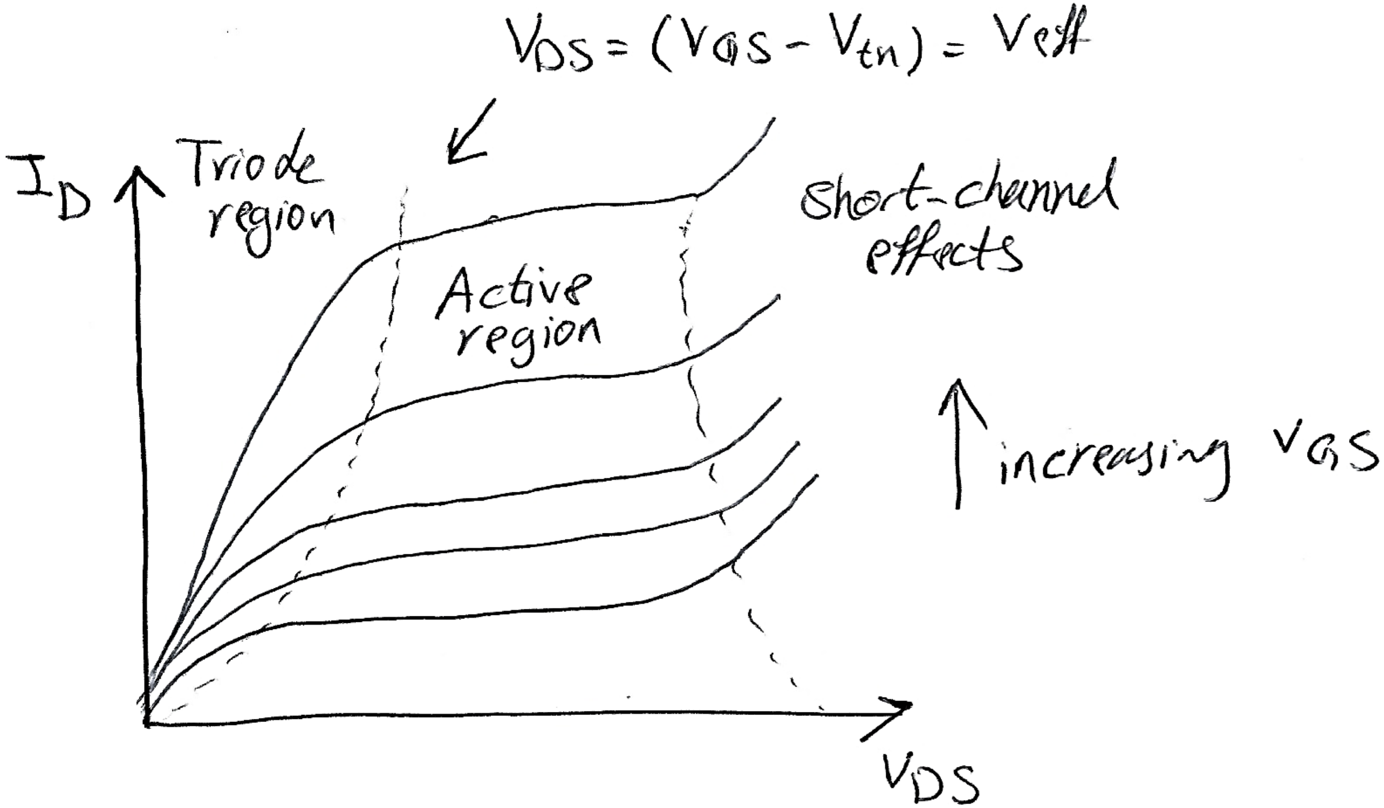


✓ Active region

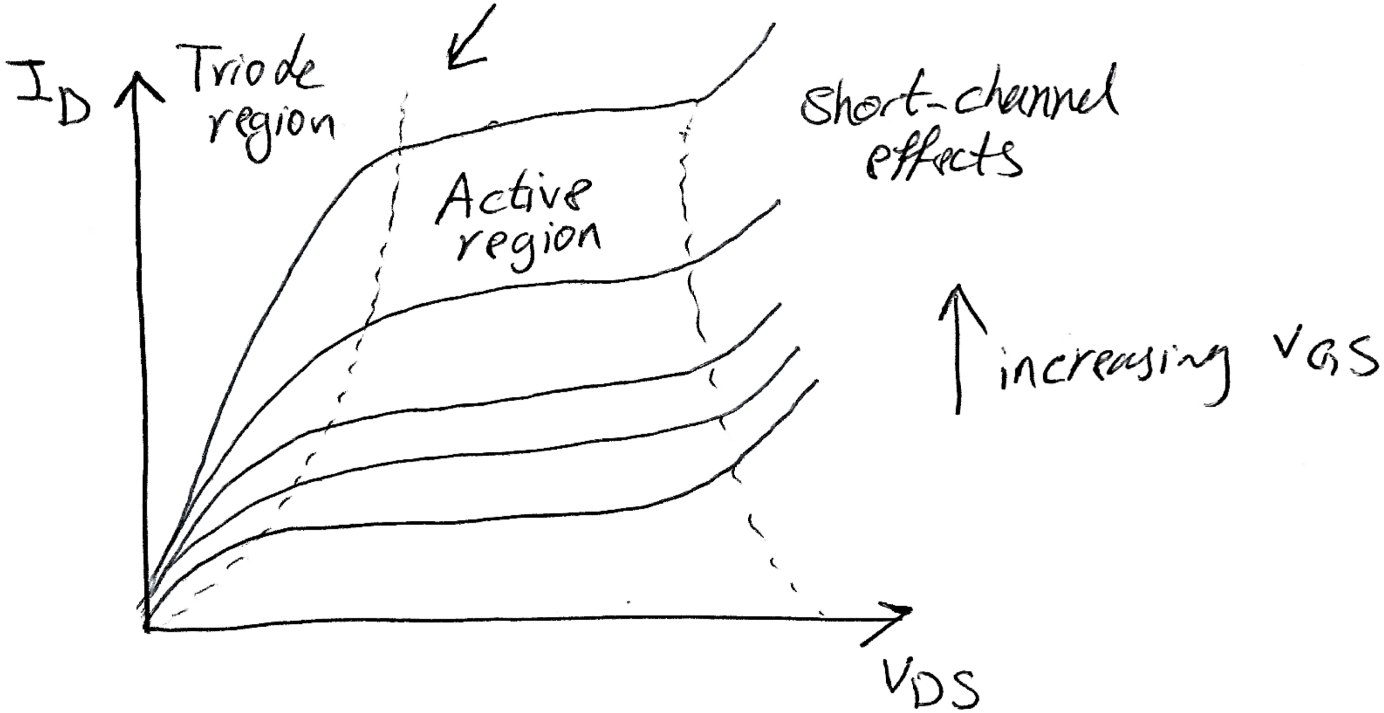
Exercise 4: determine operational mode



✓ Active region → $I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right)(V_{GS} - V_{tn})^2 (1 + \lambda (V_{DS} - V_{eff}))$

Exercise 4: determine operational mode

$V_{DS} = (V_{GS} - V_{tn}) = V_{eff}$



✓ Active region → $I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_{tn})^2 (1 + \lambda (V_{DS} - V_{eff}))$

Describes dependence of I_D to V_{DS}

Exercise 4

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

Exercise 4

$$I_D = \frac{1}{2}\,\underline{\underline{\mu_n C_{ox}}}\left(\frac{W}{L}\right)(V_{GS} - V_{tn})^2\,(1+\lambda(V_{DS} - V_{eff}))$$

$\checkmark$

$\mu_n C_{ox} = 92\ \mu A/V^2$ from table ((Given))

Exercise 4

$$I_D = \frac{1}{2} \underline{\mu_n C_{ox}} \underline{\left(\frac{W}{L}\right)} (V_{GS} - V_{tn})^2 (1 + \lambda (V_{DS} - V_{eff}))$$

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Exercise 4/

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$$\checkmark \quad \checkmark \quad \checkmark \quad \checkmark$$

$V_{tn} = 0.8\,V$ from table ((Given))

$\mu_n C_{ox} = 92\ \mu A/V^2$ from table ((Given))

Exercise 4

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

$\mu_n C_{ox}$ ✓, $\frac{W}{L}$ ✓, V_{GS} ✓, V_{tn} ✓, λ ?

$V_{tn} = 0.8\,V$ from table ((Given))

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

$\checkmark$ $\checkmark$ $\checkmark$ $\checkmark$? $\checkmark$

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$$I_D = \frac{1}{2}\underset{\checkmark}{\mu_n C_{ox}}\underset{\checkmark}{\left(\frac{W}{L}\right)}(\underset{\checkmark}{V_{GS}} - \underset{\checkmark}{V_{tn}})^2(1+\underset{?}{\lambda}(\underset{\checkmark}{V_{DS}} - \underset{\checkmark}{V_{eff}}))$$

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$$\checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad ? \quad \checkmark \quad \checkmark$$

$V_{tn} = 0.8\,V$ from table ((Given))

$\mu_n C_{ox} = 92\ \mu A/V^2$ from table ((Given))

$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS}-V_{eff}+\varphi_0}}$$

Exercise 4

$$I_D = \frac{1}{2}\underset{\checkmark}{\underline{\mu_n C_{ox}}}\left(\underset{\checkmark}{\underline{\frac{W}{L}}}\right)(\underset{\checkmark}{\underline{V_{GS}}} - \underset{\checkmark}{\underline{V_{tn}}})^2(1+\underset{?}{\underline{\lambda}}(\underset{\checkmark}{\underline{V_{DS}}} - \underset{\checkmark}{\underline{V_{eff}}}))$$

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$$k_{ds} = \sqrt{\frac{2 k_s \varepsilon_0}{q N_A}}$$

Exercise 4

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$$\checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad ? \quad \checkmark \quad \checkmark$$

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q = Elementary charg

k_s = relative permittivity of silicon

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$$\underline{\checkmark} \quad \underline{\checkmark} \quad \underline{\checkmark} \quad \underline{\checkmark} \quad \underline{?} \quad \underline{\checkmark} \quad \underline{\checkmark}$$

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$$k_{ds} = \sqrt{\frac{2 k_s \varepsilon_0}{q N_A}} = \sqrt{\frac{2 \times 11.8 \times 8.854 \times 10^{-12}}{1.602 \times 10^{-19} \times 10^{22}}}$$

q = Elementary charge

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$$I_D = \frac{1}{2} \underset{\checkmark}{\mu_n C_{ox}} \underset{\checkmark}{\left(\frac{W}{L}\right)} (\underset{\checkmark}{V_{GS}} - \underset{\checkmark}{V_{tn}})^2 (1 + \underset{?}{\lambda}(\underset{\checkmark}{V_{DS}} - \underset{\checkmark}{V_{eff}}))$$

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q = Elementary charge

k_s = relative permittivity of silicon

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$$I_D = \frac{1}{2}\,\underset{\checkmark}{\underline{\mu_n C_{ox}}}\,\underset{\checkmark}{\underline{\left(\frac{W}{L}\right)}}\,(\underset{\checkmark}{\underline{V_{GS}}} - \underset{\checkmark}{\underline{V_{tn}}})^2\,(1+\underset{?}{\underline{\lambda}}(\underset{\checkmark}{\underline{V_{DS}}} - \underset{\checkmark}{\underline{V_{eff}}}))$$

$V_{tn} = 0.8\,V$ from table ((Given))

$\mu_n C_{ox} = 92\ \mu A/V^2$ from table ((Given))

$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS} - V_{eff} + \Phi_0}}$$ ← Built-in Voltage

$$k_{ds} = \sqrt{\frac{2 k_s \varepsilon_0}{q N_A}} = \sqrt{\frac{2 \times 11.8 \times 8.854 \times 10^{-12}}{1.602 \times 10^{-19} \times 10^{22}}} = 3.612 \times 10^{-7}\ m/\sqrt{V}$$

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Exercise 4

junction built-in voldage:

$$\varphi_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \times \ln\left(\frac{10^{25} \times 10^{22}}{(1.1 \times 10^{16})^2}\right) = 0.89\ V$$

@ 300°K ⇒ 26 mV

@ 300°K = 1.1 × 10^16 Carries/m³

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one side heavily dopped.

$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS} - V_{eff} + \varphi_0}}$$

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@ $300^\circ K \Rightarrow 26$ mV

@ $300^\circ K = 1.1 \times 10^{16}$ Carries/m^3

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one side heavily dopped.

$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS} - V_{eff} + \varphi_0}} = \frac{3.612 \times 10^{-17}}{2 \times 1{,}5 \times 10^{-6}\sqrt{V_{eff} - V_{eff} + 0.9}}$$

Exercise 4/

junction built-in voltage:

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n_i: @ $300^\circ K = 1.1 \times 10^{16}$ Carriers/m^3

Hereafter we use $\varphi_0 \cong 0.9\ V$ for built-in voltage of junctions one side heavily dopped.

$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS} - V_{eff} + \varphi_0}} = \frac{3.612 \times 10^{-17}}{2 \times 1{,}5 \times 10^{-6}\sqrt{V_{eff} - V_{eff} + 0.9}} = 0.127\ V^{-1}$$

Exercise 4

$$I_D \Big|_{V_{DS} = V_{eff}}$$

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$$I_D\Big|_{V_{DS}=V_{eff}} = \frac{92}{2}\cdot\frac{50}{1.5}(1.1-0.8)^2\underbrace{(1+\lambda(V_{eff}-V_{eff}))}_{=1}$$

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((4 % increase))

Exercise 5

$$I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_{tn})^2 \left[1 + \lambda (V_{DS} - V_{eff})\right]$$

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$$I_D\Big|_{V_{DS}=V_{eff}+0.5} = 23\,\mu A = I_D\Big|_{V_{DS}=V_{eff}}(1+0.5\lambda)$$

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$$\Rightarrow \lambda = \frac{\left(\frac{23}{20}-1\right)}{0.5} = 0.3\ V^{-1}$$

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method 1: $r_{ds} = \frac{\Delta V}{\Delta I} = \frac{0.5}{3\times10^{-6}} = 167\,k\Omega$

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method 1: $r_{ds} = \frac{\Delta V}{\Delta I} = \frac{0.5}{3 \times 10^{-6}} = 167\,k\Omega$

method 2: $r_{ds} = \frac{1}{\lambda I_d} = \frac{1}{0.3 \times 20 \times 10^{-6}}$

Exercise 6

Low frequency

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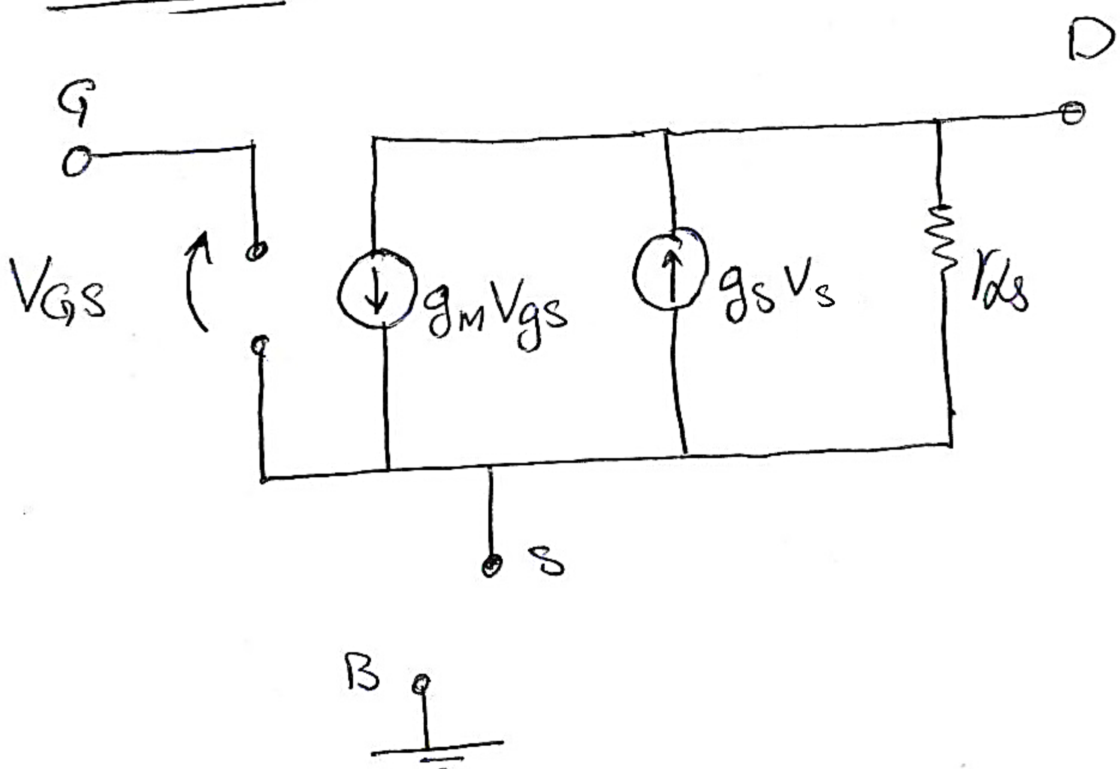
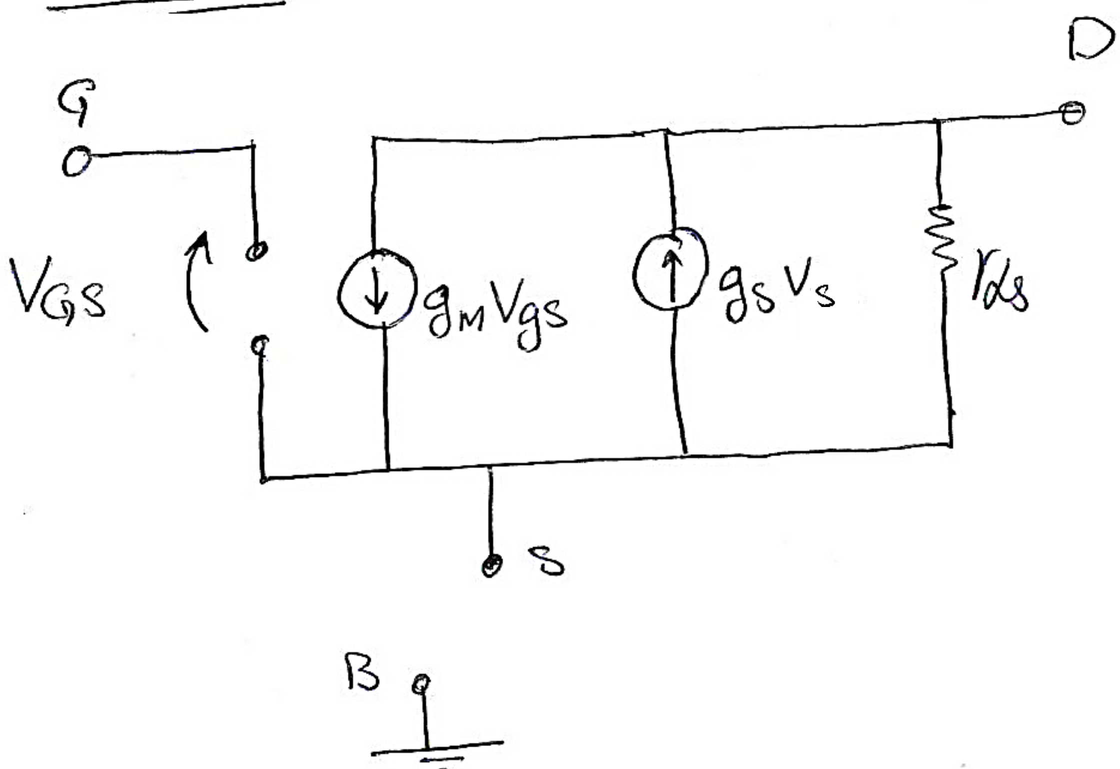
Low frequency



Exercise 6

Low frequency, find g_m, g_s and r_{ds}



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$V_{DS} = V_{eff}$ simplify everything

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$$\lambda \Big|_{V_{DS} = V_{eff}} = \frac{k_{ds}}{2L\sqrt{\Phi_0}} = \frac{3.612 \times 10^{-7}}{2 \times 1,2 \times 10^{-6} \sqrt{0.5}} = 0.159\ V^{-1}$$

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$V_{DS} = V_{eff}$ Simplify everything

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$$I_D = \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right)(V_{GS} - V_{tn})^2 = \frac{92}{2} \times \frac{10}{1.2} (1.1 - 0.8)^2 = 34.5 \ \mu A$$

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$$I_D = \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right) (V_{GS} - V_{th})^2 = \frac{92}{2} \times \frac{10}{1.2} (1.1 - 0.8)^2 = 34.5\ \mu A$$

$$\begin{cases} r_{ds} = \dfrac{1}{\lambda I_D} = 182\ k\Omega \\ g_m = \sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right) I_d} = 230\ \mu A/V \quad \text{MOS transconductance} \\ g_s = \dfrac{\gamma \cdot g_m}{2\sqrt{V_{SB} + 2\Phi_F}} \end{cases}$$

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$V_{DS} = V_{eff}$ Simplify everything

$$k_{ds} = \sqrt{\frac{2k_s \varepsilon_0}{q N_A}} = 3.612 \times 10^{-7}$$

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$$r_{ds} = \frac{1}{\lambda I_D} = 182\ k\Omega$$

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_d} = 230\ \mu A/V$$ MOS transconductance

$$g_s = \frac{\gamma \cdot g_m}{2\sqrt{V_{SB} + 2\Phi_F}}$$

γ: body effect Constant

Here $\gamma = 0.5$

$\Phi_F = V_T \ln(N_A/n_i) = 0.35V$

Exercise 6

$V_{DS} = V_{eff}$ Simplify everything

$$k_{ds} = \sqrt{\frac{2k_s \varepsilon_0}{q N_A}} = 3.612 \times 10^{-7}$$

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$$I_D = \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right) (V_{GS} - V_{tn})^2 = \frac{92}{2} \times \frac{10}{1.2} (1.1 - 0.8)^2 = 34.5\ \mu A$$

$$r_{ds} = \frac{1}{\lambda I_D} = 182\ k\Omega$$

$$g_m = \sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right) I_d} = 230\ \mu A/V$$ MOS transconductance

$$g_s = \frac{\gamma \cdot g_m}{2\sqrt{V_{SB} + 2\varphi_F}} = \frac{0.5 \times 230 \times 10^{-6}}{2\sqrt{1 + 2 \times 0.35}} = 44\ \mu A/V$$ Body effect transcoductance

γ: body effect constant

Here $\gamma = 0.5$

$\varphi_F = V_T \ln(N_A/n_i) = 0.35V$