VE311 Homework 3

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Problem 1.

(a)

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025\,\mathrm{V} \cdot \ln \frac{10^{19}\,\mathrm{cm}^{-3} \cdot 10^{18}\,\mathrm{cm}^{-3}}{(10^{10}\,\mathrm{cm}^{-3})^2} \approx 0.979\,\mathrm{V}$$

$$\begin{aligned} w_{do} &= \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j} \\ &= \sqrt{\frac{2 \cdot 11.7 \cdot 8.85 \times 10^{-14}\,\mathrm{F/cm}}{1.60 \times 10^{-19}\,\mathrm{C}}\left(\frac{1}{10^{19}\,\mathrm{cm}^{-3}} + \frac{1}{10^{18}\,\mathrm{cm}^{-3}}\right)0.979\,\mathrm{V}} \\ &\approx 3.73 \times 10^{-2}\,\mu\mathrm{m} \end{aligned}$$

(b)

$$x_p = \frac{w_{do}}{1 + \dfrac{N_A}{N_D}} = \frac{3.73 \times 10^{-2}\,\mu\mathrm{m}}{1 + \dfrac{10^{19}\,\mathrm{cm}^{-3}}{10^{18}\,\mathrm{cm}^{-3}}} \approx 3.39 \times 10^{-3}\,\mu\mathrm{m}$$

$$x_n = \frac{w_{do}}{1 + \dfrac{N_D}{N_A}} = \frac{3.73 \times 10^{-2}\,\mu\mathrm{m}}{1 + \dfrac{10^{18}\,\mathrm{cm}^{-3}}{10^{19}\,\mathrm{cm}^{-3}}} \approx 3.39 \times 10^{-2}\,\mu\mathrm{m}$$

(c)

$$\phi_j = 0.979\,\mathrm{V}$$

(d)

$$E_{MAX} = \frac{qN_A x_p}{\varepsilon_s} = \frac{1.60 \times 10^{-19}\,\mathrm{C} \cdot 10^{19}\,\mathrm{cm}^{-3} \cdot 3.39 \times 10^{-3}\,\mu\mathrm{m}}{11.7 \cdot 8.85 \times 10^{-14}\,\mathrm{F/cm}} \approx 523\,\mathrm{kV/cm}$$

Problem 2.

(a)

$$w_d = w_{do}\sqrt{1 + \frac{v_R}{\phi_j}} = 3w_{do}$$

$$v_R = 8\phi_j = 8 \cdot 0.85\,\mathrm{V} = 6.8\,\mathrm{V}$$

(b)

$$w_d = w_{do}\sqrt{1 + \frac{v_R}{\phi_j}} = 0.4\,\mu\mathrm{m} \cdot \sqrt{1 + \frac{7\,\mathrm{V}}{0.85\,\mathrm{V}}} \approx 1.22\,\mu\mathrm{m}$$

Problem 3.

$$j = \sigma E$$

$$E = \frac{j}{\sigma} = j\rho = 5000\,\mathrm{A/cm^2} \cdot 2.5\,\Omega \cdot \mathrm{cm} = 12.5\,\mathrm{kV/cm}$$

Problem 4.

$$p(x) = N_A(x) = N_o \exp\left(-\frac{x}{L}\right)$$

$$j_p^T = qp\mu_p E - qD_p \frac{\partial p}{\partial x} = qp\mu_p \left(E - V_T \frac{1}{p}\frac{\partial p}{\partial x}\right) = 0$$

$$E(x) = V_T \frac{1}{p}\frac{\partial p}{\partial x} = \frac{V_T}{N_o \exp\left(-\frac{x}{L}\right)} \cdot -\frac{N_o}{L}\exp\left(-\frac{x}{L}\right) = -\frac{V_T}{L}$$

So a built-in electric field must exist.

$$E = -\frac{V_T}{L} = -\frac{0.025\,\mathrm{V}}{1\,\mu\mathrm{m}} = -0.25\,\mathrm{kV/cm}$$

Problem 5.

$$nV_T = n\frac{kT}{q} = 1.05 \cdot \frac{1.38 \times 10^{-23}\,\mathrm{J/K} \cdot 320\,\mathrm{K}}{1.60 \times 10^{-19}\,\mathrm{C}} \approx 0.029\,\mathrm{V}$$

If $n = 1.00$,

$$nV_T = n\frac{kT}{q} = 0.029\,\mathrm{V}$$

$$T = \frac{0.029\,\mathrm{V} \cdot q}{k} = \frac{0.029\,\mathrm{V} \cdot 1.60 \times 10^{-19}\,\mathrm{C}}{1.38 \times 10^{-23}\,\mathrm{J/K}} \approx 336\,\mathrm{K}$$

Problem 6.

(a)

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) = 1.07 \cdot 0.025\,\mathrm{V} \cdot \ln\left(1 + \frac{70\,\mu\mathrm{A}}{10^{-17}\,\mathrm{A}}\right) \approx 0.791\,\mathrm{V}$$

(b)

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) = 1.07 \cdot 0.025\,\mathrm{V} \cdot \ln\left(1 + \frac{5\,\mu\mathrm{A}}{10^{-17}\,\mathrm{A}}\right) \approx 0.721\,\mathrm{V}$$

(c)

$$I_D = I_S\left[\exp\left(\frac{V_D}{nV_T}\right) - 1\right] = 10^{-17}\,\mathrm{A} \cdot \left[\exp\left(\frac{0}{1.07 \cdot 0.025\,\mathrm{V}}\right) - 1\right] = 0\,\mathrm{A}$$

(d)

$$I_D = I_S\left[\exp\left(\frac{V_D}{nV_T}\right) - 1\right] = 10^{-17}\,\mathrm{A} \cdot \left[\exp\left(\frac{-0.075\,\mathrm{V}}{1.07 \cdot 0.025\,\mathrm{V}}\right) - 1\right] \approx -9.39 \times 10^{-18}\,\mathrm{A}$$

(e)

$$I_D = I_S \left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right] = 10^{-17}\,\text{A} \cdot \left[\exp\left(\frac{-5\,\text{V}}{1.07 \cdot 0.025\,\text{V}}\right) - 1 \right] \approx -1.00 \times 10^{-17}\,\text{A}$$

Problem 7.

$$\begin{aligned} V_D &= V_T \ln\left(1 + \frac{I_D}{I_S}\right) \\ V_{D,MAX} &= V_T \ln\left(1 + \frac{I_D}{I_{S,MIN}}\right) = 0.025\,\text{V} \ln\left(1 + \frac{1\,\text{mA}}{10^{-14}\,\text{A}}\right) \approx 0.633\,\text{V} \\ V_{D,MIN} &= V_T \ln\left(1 + \frac{I_D}{I_{S,MAX}}\right) = 0.025\,\text{V} \ln\left(1 + \frac{1\,\text{mA}}{10^{-12}\,\text{A}}\right) \approx 0.518\,\text{V} \\ & 0.518\,\text{V} \leqslant V_D \leqslant 0.633\,\text{V} \end{aligned}$$

Problem 8.

(a)

$$\begin{aligned} V_D &= V_T \ln\left(1 + \frac{I_D}{I_S}\right) = \frac{kT}{q} \ln\left(1 + \frac{I_D}{I_S}\right) \\ &= \frac{1.38 \times 10^{-23}\,\text{J/K} \cdot 303\,\text{K}}{1.60 \times 10^{-19}\,\text{C}} \ln\left(1 + \frac{1\,\text{mA}}{2.5 \times 10^{-16}\,\text{A}}\right) \\ &\approx 0.758\,\text{V} \end{aligned}$$

(b)

$$\frac{dV_D}{dT} = \frac{v_D - V_{GO} - 3V_T}{T} = -2\,\text{mV/K}$$

$$\begin{aligned} V_D &= T\frac{dV_D}{dT} + V_{GO} + 3\frac{kT}{q} \\ &= 323\,\text{K} \cdot -2\,\text{mV/K} + 1.12\,\text{V} + 3 \cdot \frac{1.38 \times 10^{-23}\,\text{J/K} \cdot 323\,\text{K}}{1.60 \times 10^{-19}\,\text{C}} \\ &\approx 0.558\,\text{V} \end{aligned}$$

Problem 9.

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025\,\text{V} \cdot \ln \frac{10^{18}\,\text{cm}^{-3} \cdot 10^{20}\,\text{cm}^{-3}}{(10^{10}\,\text{cm}^{-3})^2} \approx 1.036\,\text{V}$$

$$\begin{aligned} w_{do} &= \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j} \\ &= \sqrt{\frac{2 \cdot 11.7 \cdot 8.85 \times 10^{-14}\,\text{F/cm}}{1.60 \times 10^{-19}\,\text{C}}\left(\frac{1}{10^{18}\,\text{cm}^{-3}} + \frac{1}{10^{20}\,\text{cm}^{-3}}\right) 1.036\,\text{V}} \\ &\approx 3.68 \times 10^{-2}\,\mu\text{m} \end{aligned}$$

When $v_R = 5\,\mathrm{V}$,

$$w_d = w_{do}\sqrt{1+\frac{v_R}{\phi_j}} = 3.68\times10^{-2}\,\mu\mathrm{m}\cdot\sqrt{1+\frac{5\,\mathrm{V}}{1.036\,\mathrm{V}}} \approx 8.88\times10^{-2}\,\mu\mathrm{m}$$

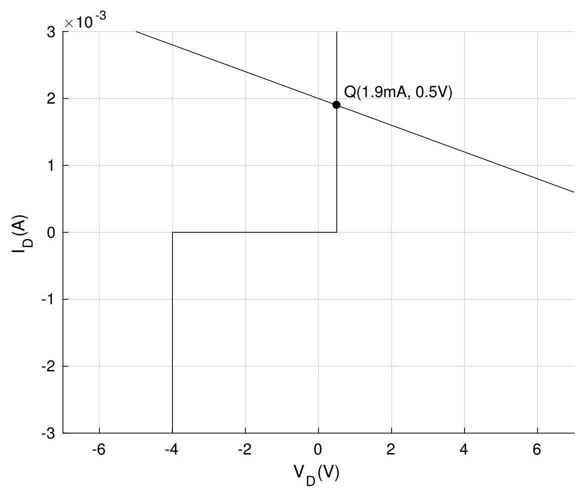
When $v_R = 25\,\mathrm{V}$,

$$w_d = w_{do}\sqrt{1+\frac{v_R}{\phi_j}} = 3.68\times10^{-2}\,\mu\mathrm{m}\cdot\sqrt{1+\frac{25\,\mathrm{V}}{1.036\,\mathrm{V}}} \approx 0.184\,\mu\mathrm{m}$$

Problem 10.

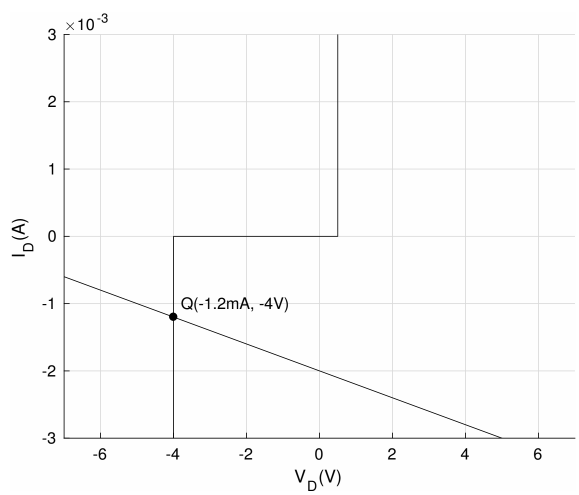
(a)

$$V_D = 0, I_D = 10\,\mathrm{V}/5\,\mathrm{k\Omega} = 2\,\mathrm{mA} \quad \text{and} \quad V_D = 10\,\mathrm{V}, I_D = 0$$



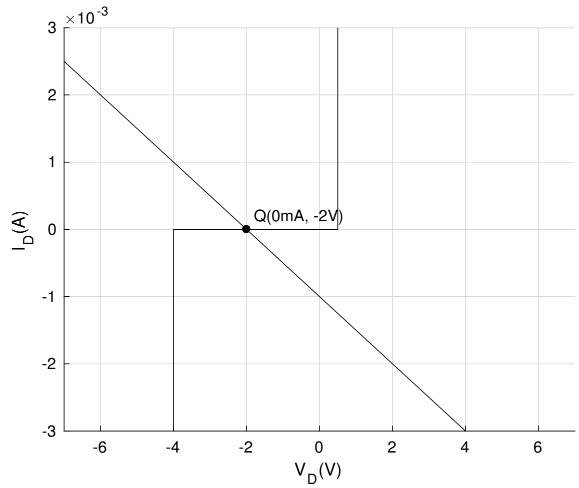
(b)

$$V_D = 0, I_D = -10\,\mathrm{V}/5\,\mathrm{k\Omega} = -2\,\mathrm{mA} \quad \text{and} \quad V_D = -10\,\mathrm{V}, I_D = 0$$



(c)

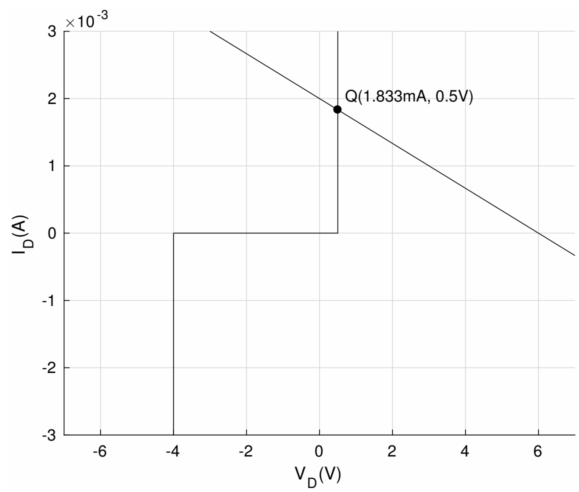
$$V_D = 0, I_D = -2\,\mathrm{V}/2\,\mathrm{k}\Omega = -1\,\mathrm{mA} \quad \text{and} \quad V_D = -2\,\mathrm{V}, I_D = 0$$



Problem 11.

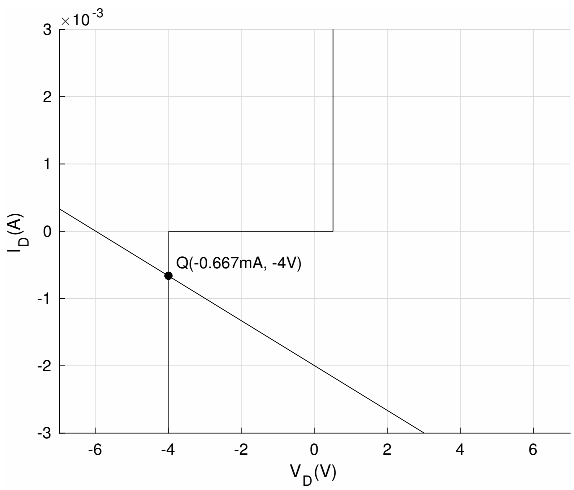
(a)

$$V_D = 0, I_D = 6\,\mathrm{V}/4\,\mathrm{k}\Omega = 1.5\,\mathrm{mA} \quad \text{and} \quad V_D = 6\,\mathrm{V}, I_D = 0$$



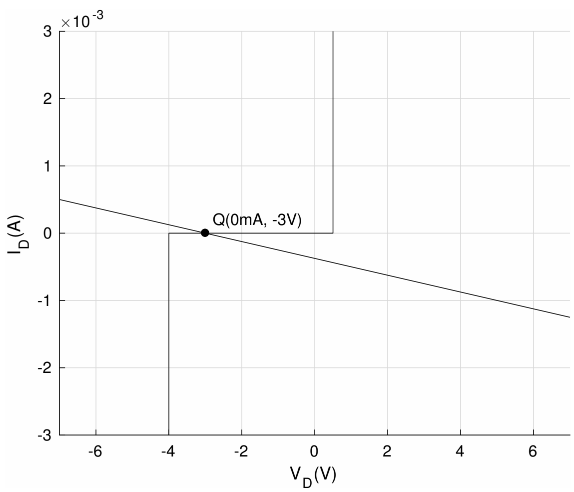
(b)

$$V_D = 0, I_D = -6\,\mathrm{V}/3\,\mathrm{k}\Omega = -2\,\mathrm{mA} \quad \text{and} \quad V_D = -6\,\mathrm{V}, I_D = 0$$



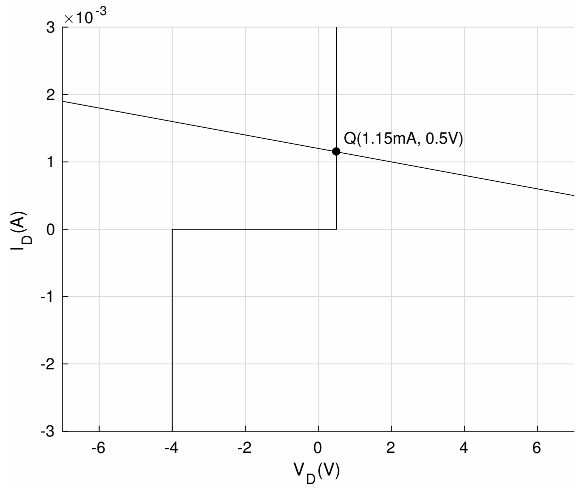
(c)

$$V_D = 0, I_D = -3\,\mathrm{V}/3\,\mathrm{k\Omega} = -1\,\mathrm{mA} \quad \text{and} \quad V_D = -3\,\mathrm{V}, I_D = 0$$



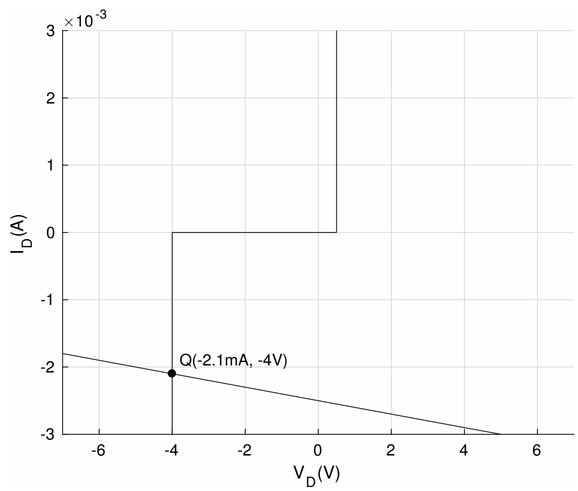
(d)

$$V_D = 0, I_D = 12\,\mathrm{V}/8\,\mathrm{k\Omega} = 1.5\,\mathrm{mA} \quad \text{and} \quad V_D = 12\,\mathrm{V}, I_D = 0$$



(e)

$$V_D = 0, I_D = -25\,\mathrm{V}/10\,\mathrm{k\Omega} = -2.5\,\mathrm{mA} \quad \text{and} \quad V_D = -25\,\mathrm{V}, I_D = 0$$



Problem 12.

When $R_S = 0$, assuming $V_{on} = 1\,\mathrm{V}$

$$V_{dc} = V_p - V_{on} = 10\,\mathrm{V} - 1\,\mathrm{V} = 9\,\mathrm{V}$$

$$\begin{cases} V_r = V_{dc}\left[1 - \exp\left(-\dfrac{T - \Delta T}{RC}\right)\right] \\ \Delta T = \dfrac{1}{\omega}\sqrt{\dfrac{2V_r}{V_p}} \end{cases} \Longrightarrow \begin{cases} V_r = 6.01\,\mathrm{V} \\ \Delta T = 2.91 \times 10^{-3}\,\mathrm{s} \end{cases}$$

$$I_P = I_{dc}\frac{2T}{\Delta T} = \frac{2V_{dc}T}{R\Delta T} = \frac{2 \cdot 9\,\mathrm{V} \cdot \dfrac{2\pi}{120\pi}\,\mathrm{s}}{0.025\,\Omega \cdot 2.91 \times 10^{-3}\,\mathrm{s}} \approx 4123\,\mathrm{A}$$

When $R_S = 0.02\,\Omega$,

Problem 13.

assuming $V_{on} = 1\,\mathrm{V}$,

$$V_1 = V_p - V_{on} = 40\,\mathrm{V} - 1\,\mathrm{V} = 39\,\mathrm{V}$$

$$V_1 = -(V_p - V_{on}) = -(40\,\mathrm{V} - 1\,\mathrm{V}) = -39\,\mathrm{V}$$