P-2.34

In strong inversion, $\varphi_s = 2\phi_F$, where

$$\phi_F = \frac{kT}{q}\ln\frac{N_A}{n_i} = 0.02586 \times \ln\frac{5\times 10^{16}}{1.02\times 10^{10}} = 0.40V\,,$$

$$\boxed{\varphi_s = 0.80V}$$

The voltage drop **is not** $V_G - \varphi_s$, because φ_s and the electric field in the oxide (thus the voltage drop across the oxide) are not zero at $V_G = 0V$. The reason is the existence of the work-function difference, which is basically a "built-in voltage", associated with a "built-in" field in the oxide. The work-function difference offsets the voltage drop across the oxide, so that zero voltage drop occurs for $V_G - \phi ms = 0$ (the "effective gate voltage" is zero). In general, the effective voltage drop between the gate and the substrate is shared between the oxide and the depletion layer at the surface region of the semiconductor. If the potential between the surface and the bulk of the semiconductor is φ_s, the remaining voltage drop occurs across the gate oxide:

$$V_{ox} = V_G - \phi_{ms} - \varphi_s\,.$$

Therefore, in order to calculate V_{ox}, the work-function difference is needed:

$$\phi_{ms} = \chi_s - \left(\chi_s + \frac{E_g}{2q} + \phi_F\right) = -\frac{1.12}{2} - 0.40 = -0.96\,,$$

$$V_{ox} = 5 - (-0.96) - 0.80\,,$$

$$\boxed{V_{ox} = 5.16V}$$

P-2.37

(a) As in Problems P-2.34 and P-2.35,

$$V_{ox} = V_G - \phi_{ms} - 2\phi_F\,,$$

where $V_G = V_{BRinv}$ for $E_{ox} = -1V/nm$ (minus sign is used, because this is an N-type semiconductor, and $V_{ox} = E_{ox}t_{ox}$ has to be negative in strong inversion):

$$V_{BRinv} = E_{ox}t_{ox} + \phi_{ms} + 2\phi_F\,.$$

Find now ϕ_F and ϕ_{ms}:

$$\phi_F = -\frac{kT}{q}\ln\frac{N_D}{n_i} = -0.02586 \times \ln\frac{10^{16}}{1.02\times 10^{10}} = -0.357V\,.$$

$$\phi_{ms} = \chi_s + E_g - \left(\chi_s + \frac{E_g}{2q} + \phi_F\right) = \frac{1.12}{2} - (-0.357) = 0.917V\,,$$

and then the breakdown voltage:

$$V_{BRinv} = -10^9 \times 80 \times 10^{-9} + 0.917 - 2 \times 0.357\,,$$

$$\boxed{V_{BRinv} = -79.80V}$$

(b) When gate oxide charge exists close to the interface, the oxide field consists of two components:

$$E_{ox} = \underbrace{E_{ox-gate}}_{\text{due to } V_G} + \underbrace{E_{ox-charge}}_{\text{due to } qN_{oc}} \cdot$$

According to the result of Problem P-2.36, the oxide charge component is

$$E_{ox-charge} = -\frac{qN_{oc}}{\varepsilon_{ox}} = -\frac{1.6 \times 10^{-19} \times 5 \times 10^{15}}{3.9 \times 8.85 \times 10^{-12}} = 0.0232\ V/nm\,,$$

which means the gate-voltage component of the breakdown field is

$$E_{ox-gate} = E_{ox} - E_{ox-charge} = 1 - 0.0232 \approx 0.98V/nm\,.$$

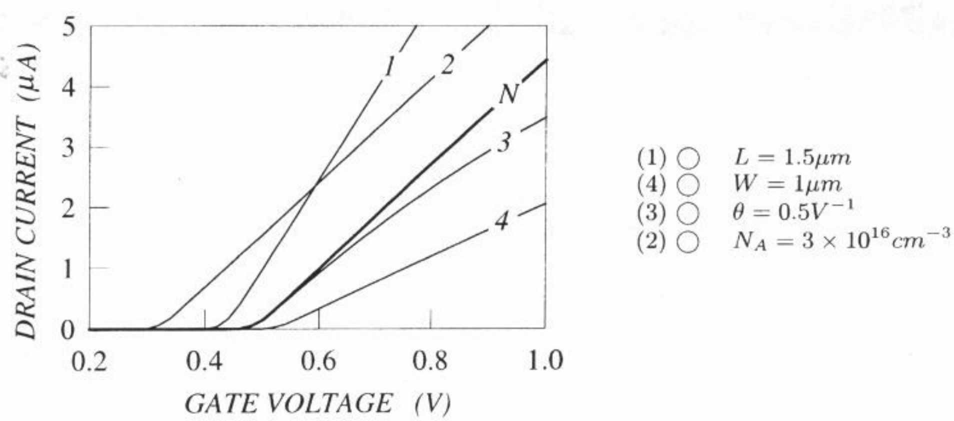
The breakdown voltage is then

$$V_{BRinv} = E_{ox-gate}t_{ox} + \phi_{ms} + 2\phi_F =$$

$$= -0.98 \times 10^9 \times 80 \times 10^{-9} + 0.917 - 2 \times 0.357\,,$$

$$\boxed{V_{BRinv} = -78.20V}$$

P-5.15



A decrease in both L and N_A results in a current increase for the same gate voltage. However, a decrease in L mostly affects the slope of the transfer characteristic (through the gain factor β), although it also reduces the threshold voltage due to short-channel charge sharing. A decrease in N_A does not significantly influence the slope, it basically reduces the threshold voltage.

Both, a smaller W and an increased θ, reduce the current for a given gate voltage. However, the effect of θ is insignificant for gate voltages not much larger than V_T. On the other hand, a smaller W proportionally reduces the current at any gate voltage, and in addition, it increases the threshold voltage due to the narrow-channel effect.

P-5.4

(a) $V_{GS} = V_{FB} = -0.75V$:

$$\boxed{\varphi_s = 0,\ Q_d = 0.}$$

(b) $V_{GS} = -0.5V$ and $V_{GS} = 0V$:
The depletion layer width is

$$w_d = \sqrt{\frac{2\varepsilon_s}{qN_A}\varphi_s}\,,$$

so that

$$Q_d = qN_A w_d = \sqrt{2\varepsilon_s q N_A \varphi_s}\,.$$

As the gate oxide field is

$$E_{ox} = \frac{V_{ox}}{t_{ox}} = \frac{\overbrace{V_{GS} - V_{FB}}^{\text{effective gate voltage}} \quad -\varphi_s}{t_{ox}}\,,$$

the condition

$$\varepsilon_{ox} E_{ox} = qN_A w_d\,,$$

leads to the following equation:

$$\underbrace{\frac{\varepsilon_{ox}}{t_{ox}}}_{C_{ox}}(V_{GS} - V_{FB} - \varphi_s) = \sqrt{2\varepsilon_s q N_A}\sqrt{\varphi_s}\,,$$

$$V_{GS} - V_{FB} - \varphi_s = \underbrace{\frac{\sqrt{2\varepsilon_s q N_A}}{C_{ox}}}_{\gamma}\sqrt{\varphi_s}$$

$$\varphi_s - \gamma\sqrt{\varphi_s} - (V_{GS} - V_{FB}) = 0\,.$$

The solution of the above equation is:

$$\varphi_s = \left(\frac{\gamma - \sqrt{\gamma^2 + 4(V_{GS} - V_{FB})}}{2}\right)^2\,.$$

Mathematically, there is an additional solution, with "+" in front of the square root, however, that solution is not physically justified – it does not provide $\varphi_s = 0$ for $V_{GS} = V_{FB}$. Therefore,

$$\gamma = \sqrt{\frac{2\varepsilon_s q N_A}{C_{ox}}} = \frac{\sqrt{2 \times 11.8 \times 8.85 \times 10^{-12} \times 1.6 \times 10^{-19} \times 5 \times 10^{22}}}{\frac{3.9 \times 8.85 \times 10^{-12}}{5 \times 10^{-9}}} =$$

$$= 0.187 V^{1/2} ,$$

$$\varphi_s = \left(\frac{0.187 - \sqrt{0.187^2 + 4 \times (-0.5 + 0.75)}}{2} \right)^2 = 0.172V \text{ for } V_{GS} = -0.5V,$$

$$\varphi_s = \left(\frac{0.187 - \sqrt{0.187^2 + 4 \times 0.75}}{2} \right)^2 = 0.605V \text{ for } V_{GS} = 0V,$$

$$Q_d = \underbrace{\sqrt{2\varepsilon_s q N_A}}_{1.293 \times 10^{-3}} \sqrt{\varphi_s} = 5.36 \times 10^{-4} C/m^2 \text{ for } V_{GS} = -0.5V ,$$

$$Q_d = 1.293 \times 10^{-3} \times \sqrt{0.605} = 1.01 \times 10^{-3} C/m^2 \text{ for } V_{GS} = 0V .$$

$$\boxed{\varphi_s = 0.172V,\ Q_d = 5.36 \times 10^{-4} C/m^2 \text{ for } V_{GS} = -0.5V.}$$

$$\boxed{\varphi_s = 0.605V,\ Q_d = 1.01 \times 10^{-3} C/m^2 \text{ for } V_{GS} = 0V.}$$

(c),(d) $V_G \geq V_T = 0.2V$:

At the onset of the threshold voltage and beyond, the surface potential is $2\phi_F$:

$$\varphi_s = 2\phi_F = 2V_t \ln \frac{N_A}{n_i} = 2 \times 0.02586 \times \ln \frac{5 \times 10^{16}}{1.02 \times 10^{10}} = 0.797V ,$$

and

$$Q_d = 1.293 \times 10^{-3} \times \sqrt{0.797} = 1.15 \times 10^{-3} C/m^2 .$$

$$\boxed{\varphi_s = 0.797V,\ Q_d = 1.15 \times 10^{-3} C/m^2.}$$

The plots are shown in Fig. M.7.

P-5.8

This is a P-channel MOSFET.

$$V_T = V_{FB} - |2\phi_F| - \gamma\sqrt{|2\phi_F| + |V_{SB}|} ,$$

$$|2\phi_F| = 2V_t \ln \frac{N_D}{n_i} = 2 \times .02586 \times \ln \frac{5 \times 10^{15}}{1.02 \times 10^{10}} = 0.678V ,$$

$$\gamma = \frac{\sqrt{2\varepsilon_s q N_D}}{C_{ox}} ,$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12}}{3.5 \times 10^{-9}} = 9.86mF/m^2 ,$$

$$\frac{\sqrt{2 \times 11.8 \times 8.85 \times 10^{-12} \times 1.6 \times 10^{-19} \times 5 \times 10^{21}}}{9.86 \times 10^{-3}} = 0.0414V^{1/2} . = \gamma$$

(a) $V_{BS} = 0V$:

$$V_T(0) = 0.2 - 0.678 - 0.0414\sqrt{0.678} = -0.51V .$$

For $V_{GS} = 0$ and $V_{GS} = 0.75V$, this MOSFET is not in strong inversion, therefore $Q_I = 0$.
For $V_{GS} = -0.75V$:

$$Q_I = C_{ox}|V_{GS} - V_T| = 9.86 \times 10^{-3} \times |-0.75 + .51| = 2.367mC/m^2 .$$

$$\boxed{Q_I = 2.37mC/m^2 \text{ for } V_{GS} = -0.75V;\ Q_I = 0 \text{ for } V_{GS} = 0 \text{ and } 0.75V}$$

(b) $V_{BS} = 0.75V$:

$$V_T(0.75) = 0.2 - 0.678 - 0.0414\sqrt{0.678 + 0.75} = -0.53V ,$$

$$Q_I = 9.86 \times 10^{-3} \times |-0.75 + .53| = 2.367mC/m^2 .$$

$$\boxed{Q_I = 2.17mC/m^2 \text{ for } V_{GS} = -0.75V;\ Q_I = 0 \text{ for } V_{GS} = 0 \text{ and } 0.75V}$$