H·W-3

4.1

$N_A = 9.6 \times 10^{18}\ cm^{-3}$ $\quad x_j = 0.02\ \mu m$

$N_{A(sw)} = 7.46 \times 10^{15}\ cm^{-3}$ $\quad t_{ox} = 6\ \mathring{A}$

$N_D = 4.8 \times 10^{17}\ cm^{-3}$ $\quad L_D = 4nm$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-14}}{6 \times 10^{-8}} = 5.75 \times 10^{-6}\ [F/cm^2]$$

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_{si}}}{C_{ox}} = \frac{\sqrt{2 \times 1.6 \times 10^{-19} \times 9.6 \times 10^{18} \times 11.7 \times 8.85 \times 10^{-14}}}{5.75 \times 10^{-6}}$$

$$\gamma = \frac{1.783 \times 10^{-6}}{5.75 \times 10^{-6}} = 0.31\ [V^{1/2}]$$

$$|2\phi_F\,(\text{substrate})| = \left|2\frac{KT}{q}\ln\frac{n_i}{N_A}\right| = \left|2 \times 0.026 \times \ln\frac{1.45 \times 10^{10}}{9.6 \times 10^{18}}\right|$$

$$|2\phi_F\,(\text{substrate})| = 1.05\ [V]$$

$$\phi_0 = \frac{KT}{q}\ln\frac{N_A N_D}{n_i^2} = 0.026\ \ln\left[\frac{9.6 \times 10^{18} \times 4.8 \times 10^{17}}{(1.45 \times 10^{10})^2}\right]$$

$$\phi_0 = \cancel{0.026}\ 0.978\ [V]$$

$$\phi_{0sw} = \frac{KT}{q}\ln\left[\frac{N_{A(sw)} \cdot N_D}{n_i^2}\right] = 0.026 \times \ln\left[\frac{7.46 \times 10^{15} \times 4.8 \times 10^{17}}{(1.45 \times 10^{10})^2}\right]$$

$$\phi_{0(sw)} = 0.792\ [V]$$

$$C_{j0} = \sqrt{\frac{\varepsilon_{si} \cdot q}{2}\left(\frac{N_A \cdot N_D}{N_A + N_D}\right) \cdot \frac{1}{\phi_0}}$$

$$= \sqrt{\frac{11.7 \times 8.85 \times 10^{-14} \times 1.6 \times 10^{-19}}{2} \cdot \left(\frac{9.6 \times 10^{18} \times 4.8 \times 10^{17}}{9.6 \times 10^{18} + 4.8 \times 10^{17}}\right) \cdot \frac{1}{0.978}}$$

$$= \frac{873.73}{4.44 \times 10^{9}}$$

$$C_{j0} = 1.96 \times 10^{-7} \, [F/cm^2] = 1.96 \times 10^{-3}$$

$$C_{jsw} = X_j \cdot \sqrt{\frac{\varepsilon_{si} \cdot q}{2}\left(\frac{N_{A(sw)} \cdot N_D}{N_{A(sw)} + N_D}\right) \cdot \frac{1}{\phi_{0sw}}}$$

$$= 0.02 \times 10^{-4} \sqrt{\frac{11.7 \times 8.85 \times 10^{-14} \times 1.6 \times 10^{-19} (7.46 \times 10^{15} \times 4.8 \times 10^{17})}{2(7.46 \times 10^{15} + 4.8 \times 10^{17})} \cdot \frac{1}{0.792}}$$

$$= \cancel{0.02 \times 10^{-4} \times 24.35}$$

$$C_{jsw} = 5.54 \times 10^{-14} \, [F/cm] = 5.54 \times 10^{-12} \, [F/m]$$

$$C_{GSO} = C_{GDO} = C_{ox} \cdot L_D = 5.75 \times 10^{-6} \times 4 \times 10^{-7}$$

$$= 23 \times 10^{-13} \, [F/cm]$$

$$= 23 \times 10^{-11} \, [F/m]$$

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Spice netlist:

M1 6 12 4 7 NM1 W=200N L=120N
LD=9N AS=0.058P PS=0.98U
AD=0.1492P PD=1.7U

MODEL NM1 NMOS (VTO=0.53 KP=98.2U
LAMDA=0.08 GAMMA=0.31 PHI=0.978
PB=0.792 CJ=1.96E-3 CJSW=5.54E-12
C_{GSO}=23E-11 C_{GDO}=23E-11 MJ=0.5
MJSW=0.33)

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4.3

Derivation:

Sensitivity of drain current with respect to Temperature T can be expressed by:

$$\frac{\partial I_D}{\partial T} = \frac{\partial I_D}{\partial \mu_n} \cdot \frac{\partial \mu_n}{\partial T} + \frac{\partial I_D}{\partial V_T} \cdot \frac{\partial V_T}{\partial T}$$

where in SPICE level 1 model,

$$\frac{\partial I_D}{\partial \mu_n} = \frac{I_D}{\mu_n}$$

The mobility temperature dependence is:

$$\mu_n(T) = \frac{\mu_n(300K)}{\left(T/300\right)^{3/2}}$$

$$\frac{\partial \mu_n}{\partial T} = \frac{-\mu_n(300k)}{200} \cdot \left(\frac{T}{300}\right)^{-5/2}$$

For simplicity, assume $V_{SB} = 0V$,

$$V_T = V_{T0} = \phi_{GC} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}$$

$$\frac{\partial V_T}{\partial T} = \frac{\partial \phi_{GC}}{\partial T} - 2\frac{\partial \phi_F}{\partial T} - \frac{1}{C_{ox}} \cdot \frac{\partial Q_{B0}}{\partial T}$$

$$\phi_F = \frac{kT}{q} \ln \frac{n_i}{N_A}$$

$$\frac{\partial \phi_F}{\partial T} = \frac{\phi_F}{T}$$

$$\phi_{GC} = \frac{kT}{q} \ln \frac{n_i^2}{N_A \cdot N_D}$$

$$\frac{\partial \phi_{GC}}{\partial T} = \frac{\phi_{GC}}{T}$$

$$Q_{B0} = \sqrt{2 q N_A \varepsilon_{si} \cdot |2\phi_F|}$$

$$\frac{\partial Q_{B0}}{\partial T} = \frac{-1}{2} \frac{Q_{B0}}{\phi_F} \frac{\partial \phi_F}{\partial T} = \frac{-1}{2} \frac{Q_{B0}}{T}$$

In linear region,

$$\frac{\partial I_D}{\partial V_T} = \frac{-\mu_n C_{ox}}{2} \frac{W}{L_{eff}} (1+\lambda V_{DS})(2V_{DS})$$

Therefore,

$$\frac{\partial I_D}{\partial V_T} = \frac{-I_D}{\mu_n} \cdot \frac{\mu_n(300k)}{200} \cdot \left(\frac{T}{300}\right)^{-5/2}$$

$$-\frac{\mu_n C_{ox}}{2} \frac{W}{L_{eff}} (1+\lambda V_{DS})(2V_{DS}) \left[\frac{\partial \phi_{GC}}{\partial T} - 2\frac{\partial \phi_F}{\partial T} - \frac{1}{C_{ox}} \frac{\partial Q_{B0}}{\partial T}\right]$$

In Saturation Region,

$$\frac{\partial I_D}{\partial V_T} = -\mu_n C_{ox} \frac{W}{L_{eff}} (1+\lambda V_{DS})(V_{GS}-V_T)V_T \longrightarrow 1$$

$$\frac{\partial I_D}{\partial V_T} = -\frac{I_D}{\mu_n} \frac{\mu_n(300k)}{200} \cdot \left(\frac{T}{300}\right)^{-5/2}$$

$$-\mu_n C_{ox} \frac{W}{L_{eff}} (1+\lambda V_{DS})(V_{GS}-V_T) V_T \left[\frac{\partial \phi_{GC}}{\partial T} - 2\frac{\partial \phi_F}{\partial T} \frac{-1}{C_{ox}} \frac{\partial Q_{BO}}{\partial T}\right]$$

At 300K, when $V_{DS} = 1.2V$, $V_{BS} = 0V$, the transistor is saturated.

Use the saturation current eq^n and plug in the respective values. $\rightarrow$ step 1

Then calculate $\frac{\partial I_D}{\partial V_T}$ in saturation region by using eq^n 1

Then calculate $\mu_n = \frac{K'}{C_{ox}}$ $\Rightarrow$ step-2.

Then calculate $\frac{\partial I_D}{\partial \mu_n} = \frac{I_D}{\mu_n}$ { I_D & μ_n calculated in step 1 & step 2 }

$$\frac{\partial \mu_n}{\partial T} = \frac{-\mu_n}{200}$$

$$\frac{\partial V_T}{\partial T} = \frac{\phi_{GC}}{T} - \frac{2\phi_F}{T} + \frac{1}{2C_{ox}} \cdot \frac{Q_{BO}}{T}$$

Calculate I_D at $T = 310K$;

Calculat ϕ_F, ϕ_{GC}, $\frac{Q_{B0}}{C_{ox}}$ $(V_{T0} = 0.53V)$

using the equations described in the derivation section.

$$\mu_n(310K) = \frac{\mu_n(300k)}{\left(\frac{310}{300}\right)^{3/2}}$$

Then use I_D eq^n in saturation region.