ECE 643 — Exam #1

Due: **noon EDT, Wednesday 2 October 2002**

20 points

1. Assume a silicon substrate is uniformly doped with a dopant concentration of 10^{18} cm^{-3}. What is the average distance between doping atoms?

2. Consider an abrupt Si p$^+$–n diode. Will the built–in potential increase or decrease as the temperature is raised from 20 to 100°C?

3. Consider a n$^+$–p diode, with the n$^+$ emitter side being wide compared with its hole diffusion length and the p base side being narrow compared with its electron diffusion length. Let C_{Dn} be the diffusion capacitance due to electrons stored in the base and C_{Dp} be the diffusion capacitance associated with holes stored in the emitter. If the emitter has a doping concentration of 10^{20} cm^{-3} and the base has a doping concentration of 10^{17} cm^{-3}. The base width is 100nm.

   (a) Ignoring the heavy-doping effect, evaluate
   $$\frac{C_{Dn}}{C_{Dp}} = \frac{N_E}{N_B}\frac{W_B}{2L_{pE}}$$
   for the n$^+$–p diode.

   (b) When the heavy–doping effect can not be ignored, the intrinsic carrier concentration n_i can be approximated by:
   $$n_{ie}^2 = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right)$$
   where ΔE_g is the apparent bandgap narrowing and is plotted in Figure 6.3 in FMD. Show that when the heavy–doping effect is included, the capacitance ratio becomes:
   $$\frac{C_{Dn}}{C_{Dp}} = \left(\frac{n_{ieB}^2}{n_{ieE}^2}\right)\left(\frac{N_E}{N_B}\right)\frac{W_B}{2L_{pE}}$$
   where B denotes the base and E the emitter

(c) Evaluate $\frac{C_{Dn}}{C_{Dp}}$ for the above n^+–p diode when heavy–doping effects can not be ignored,

4. Near the surface of a MOS capacitor, only the term

$$\exp\left(\frac{q\psi}{kT}\right)$$

needs to be considered when evaluating the electric field under strong inversion.

$$\frac{d\psi}{dx} = -\sqrt{\frac{2kTN_a}{\epsilon_{Si}}\left(\frac{q\psi}{kT} + \frac{N_i^2}{N_a^2}\exp\left(\frac{q\psi}{kT}\right)\right)}$$

(a) Solve for $\psi(x)$ under this condition with the boundary conditions $\psi(0) = \psi_s$

(b) Express the inversion electron concentration $n(x)$ in terms of the surface concentration

$$n(0) = \frac{N_i^2}{N_a}\exp\left(\frac{q\psi_s}{kT}\right)$$

ECE 643 — Exam #3

Due: Wednesday 18 December 2002

100 points

Assume the temperature is 25°C for all calculations. The base transport factor (the fraction of electrons traversing the base) for an n–p–n transistor is given by:

$$\alpha_T = \frac{J_n(x = W_B)}{J_n(x = 0)} \tag{1}$$

and the emitter injection efficiency γ is defined as:

$$\gamma = \frac{J_n(0)}{J_n(0) + J_p(0)} \tag{2}$$

where the intrinsic base layer is located between $x = 0$ and $x = W_B$. The common emitter β is defined as:

$$\beta = \frac{I_C}{I_B} \tag{3}$$

1. Consider a Si n–p–n transistor biased in the forward active mode with $V_{BE} = 0.5$V. The emitter–base electron–diffusion current is found to be 2mA, the base recombination current is 0.017mA, the space–charge recombination current is 0.025mA, the emitter–base hole–diffusion current is 0.072mA.

   (a) What is α_T? (5 pts)

   (b) What is γ? (5 pts)

   (c) What is β? (5 pts)

   If V_{BE} is increased to 0.6V

   (d) What is α_T? (5 pts)

   (e) What is γ? (5 pts)

   (f) What is β? (5 pts)

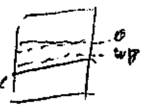
   Explain your answers.

2. A Si n–p–n transistor has $W_B = 200\text{nm}$ and the base region is uniformly doped with $N_B = 3 \times 10^{17}$ cm^{-3}. Assume the electron current in the base is due to diffusion currents only.

   (a) Derive an expression for α_T in terms of W_B and L_{nB} (the minority carrier diffusion length) (20 pts)

   (b) Calculate α_T for the transistor (5 pts)

   (c) Calculate the Base Gummel number G_B for the transistor (5 pts) $G_B = \int_0^{W_B} \left(\frac{n_i}{n_{ic}}\right)^2 \frac{p_p}{D_{np}} dx$

   (d) Under these conditions, is it safe to ignore recombination in the intrinsic base region? (5 pts)

3. For the Si n–p–n transistor in problem 2, suppose the base doping concentration is linearly graded across the base region. can't ignore drift current

   Matlab (a) Plot the total built–in electric field as a function of x between $x = 0$ and $x = W_B$ if $N_B(0) = 1 \times 10^{18}$ and $N_B(W_B) = 1 \times 10^{17}$ cm^{-3}. Are heavy–doping effects important under these conditions? (10 pts)

   (b) Estimate α_T for the transistor (10 pts) Know 3×10^{17} should tell if it is up or down & reasonally close

4. Consider two Si n–p–n transistors, one with a very–heavily doped emitter. Which of the following is true regarding the emitter injection efficiency γ for the transistor with the very–heavily doped emitter (15 pts):

   (a) γ decreases due to increased current injected from the base into the emitter

   (b) γ increases due to decreased current injected from the base into the emitter

   (c) γ decreases due to decreased current injected from the emitter to the base

   (d) γ increases due to increased current injected from the emitter to the base

   Justify your answer.

ECE 643 — Final Exam

Due: Wednesday 18 December 2002

100 points

Assume the temperature is 25°C for all calculations.

1. (30 pts) Consider a n–MOS transistor. Over time, electrons will be injected from the silicon into the SiO_2 gate dielectric causing reliability problems. If the total electron trap charge density is $N_T = 1 \times 10^{13}$ cm^{-3} and the capture cross–section of traps $\sigma = 5 \times 10^{-14}$ cm^2, the density of trapped electrons $e_T(t)$, at any give time, can be described by:

$$\frac{de_T(t)}{dt} = \frac{\sigma}{q} J_G(t)\left(N_T - e_T(t)\right) \tag{1}$$

where $J_G(t)$ is the current density through the gate. If $e_T(0) = 0$ and

$$J_G(t) = 10^{-6} \sin^2(2\pi f t) \quad A/cm^{-2}, \tag{2}$$

plot $e_T(t)$ as a function of time for f = 1MHz and f =1GHz. How long does it take to fill 1% of the trapped states when f = 1MHz and f =1GHz?

.5 x10^-7 s .5 x10^-10

2. Consider a n^+–p diode with an emitter doping concentration of 10^{20} cm^{-3} and a base doping concentration of 10^{17} cm^{-3}. Assume both the emitter and the base to be wide compared to the minority–carrier diffusion lengths.

pg 46 - 47

   (a) Calculate the electron and hole saturation current densities ignoring heavy–doping effects (5 pts)

   (b) Calculate the electron and hole saturation current densities including heavy–doping effects (5 pts)

   If the quasineutral n^+ region is only 0.1μm

   (c) Calculate the electron and hole saturation current densities ignoring heavy–doping effects (5 pts)

   (d) Calculate the electron and hole saturation current densities including heavy–doping effects (5 pts)

   (e) Calculate the capacitance ratio $\frac{C_{Dn}}{C_{Dp}}$ ignoring heavy–doping effects (5 pts)

   (f) Calculate the capacitance ratio $\frac{C_{Dn}}{C_{Dp}}$ including heavy–doping effects (5 pts)

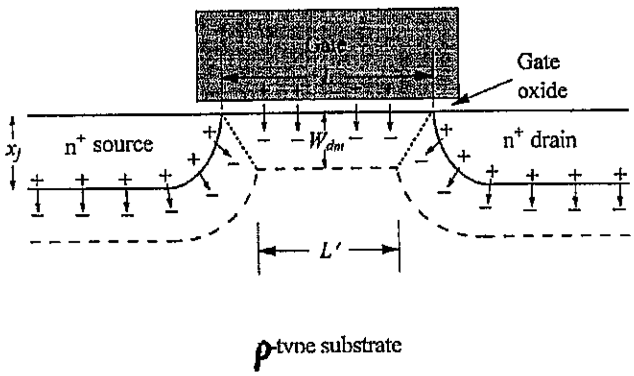


Figure 1: Charge sharing model — Figure 3.19 in FMD

3. (20 pts) Use the charge sharing model for short channel MOSFETs illustrated in the figure above. Assume that the source and drain depletion depths are equal to the gate depletion width W_{dm} and the junction curvatures under the gate edges are cylindrical. Show that

$$\frac{L+L'}{2L} = 1 - \frac{x_j}{L}\left(\sqrt{1+\frac{2W_{dm}}{x_j}} - 1\right) \tag{3}$$

In the linear regime, V_t is largely determined by the total integrated depletion charge under the gate. Show that the short–channel threshold roll–off is given by:

$$\Delta V_t(SCE) = \frac{qN_aW_{dm}}{C_{ox}}\left(\sqrt{1+\frac{2W_{dm}}{x_j}} - 1\right)\frac{x_j}{L} \tag{4}$$

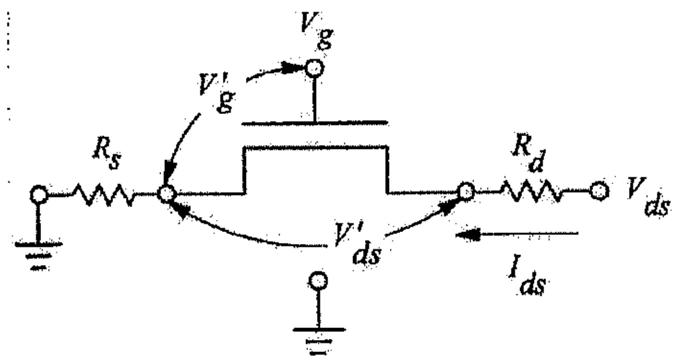


Figure 2: MOSFET Equivalent Circuit — Figure 4.20 in FMD

4. (20 pts) Consider the equivalent circuit shown above. The source–drain current can be considered either as a function of the internal voltages: $I_{ds}(V_g', V_{ds}')$ or as a function of the external voltages: $I_{ds}(V_g, V_{ds})$. The internal voltages are related to the external voltages by:

$$V_{ds}' = V_{ds} - (R_s + R_d)I_{ds} \tag{5}$$

and

$$V_g' = V_g - R_s I_{ds} \tag{6}$$

Show that the transconductance of the intrinsic MOSFET can be expressed as:

$$g_m' = \left(\frac{\partial I_{ds}}{\partial V_g'}\right)_{V_{ds}'} = \frac{g_m}{1 - g_m R_s - g_{ds}(R_s + R_d)} \tag{7}$$

where

$$g_m = \left(\frac{\partial I_{ds}}{\partial V_g}\right)_{V_{ds}} \tag{8}$$

and

$$g_{ds} = \left(\frac{\partial I_{ds}}{\partial V_{ds}}\right)_{V_g} \tag{9}$$

5. (10 pts) Optional Extra Credit: FMD 3.10