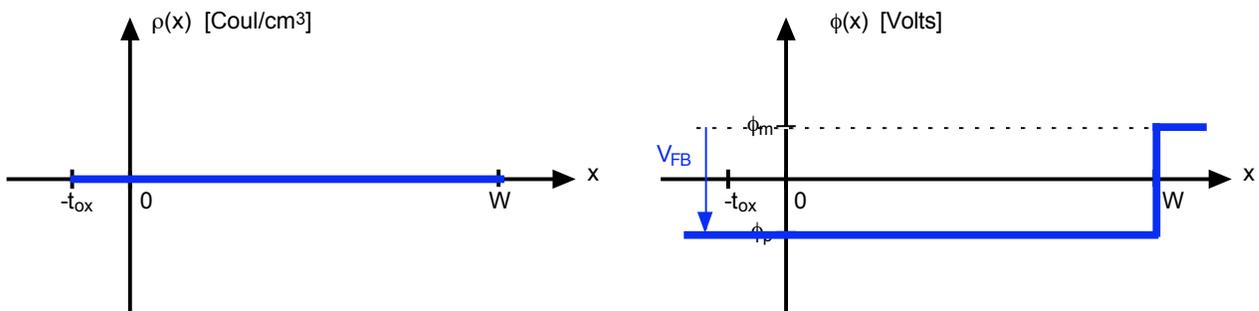


6.012 MICROELECTRONIC DEVICES AND CIRCUITS

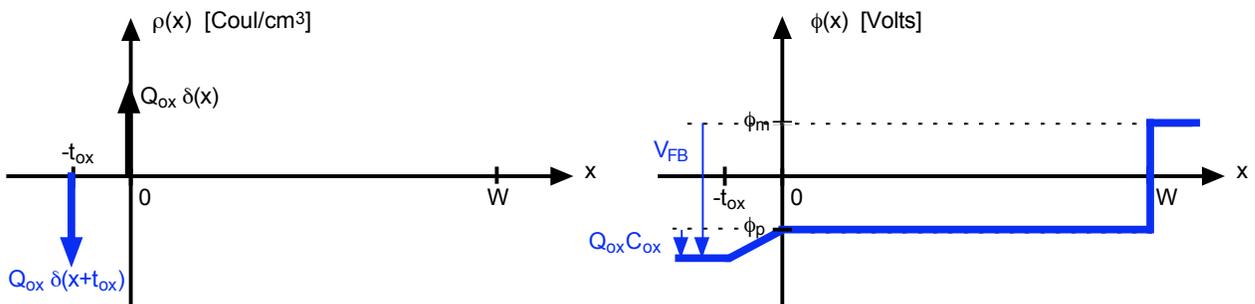
Answers to Exam 1 - Spring 2008

Problem 1: Graded by Prof. Palacios

- a) i) In the steady state the low level injection, zero current continuity equation reduces to $n' / \tau_{\min} = g_L$. Thus $\tau_{\min} = n' / g_L = 10^{14} / 10^{20} = 10^{-6} \text{ s} = 1 \mu\text{s}$.
- ii) $p = p_o + p'$ and $n = n_o + n'$; and $p_o = 10^{17} \text{ cm}^{-3}$ and $n_o = n_i^2 / p_o = 10^3 \text{ cm}^{-3}$. With $n' = p' = 10^{14} \text{ cm}^{-3}$, we have $p \approx p_o = 10^{17} \text{ cm}^{-3}$ and $n \approx n' = 10^{14} \text{ cm}^{-3}$.
- iii) After the excitation is extinguished the excess minority carrier population (actually both excesses, of course) decays as $n'(t) = n'(0)\exp(-t/\tau_{\min})$, which is the homogeneous solution of the low level continuity equation. In the present case this means $n'(t) = 10^{14}\exp(-t/\tau_{\min}) \text{ cm}^{-3}$.
- iv) Faster, because the contact introduces an interface at which any excess minority carrier encountering it recombines immediately, so the overall recombination in the solid increases and thus the rate of decay must also increase. Because the sample is small, and the bulk lifetime is relatively large, it can be assumed that the increase will not be negligibly small.
- b) i) $V_{\text{FB}} = \phi_p - \phi_m = -0.36 - 0.30 = -0.66 \text{ V}$



ii) $V_{\text{FB}} = \phi_p - \phi_m - Q_{\text{ox}} / C_{\text{ox}}^* = -0.66 - 2 \times 10^{-8} (3 \times 10^{-6} / 3.5 \times 10^{-13}) = -0.66 - 0.17 = -0.83 \text{ V}$



- c) The built-in potential is determined by the doping levels on either side of the junction so we first determine N_{Dn} from ϕ_b and N_{Ap} . From N_{Ap} we find that $\phi_p = 0.42$ V, which in turn tells us that ϕ_n must equal 0.36 V to make ϕ_b 0.78 V. This immediately tells us $N_{Dn} = 10^{16} \text{ cm}^{-3}$.

Next, w_n must be adjusted to get the desired current. One way to do this is to first calculate the electron current density at the specified bias ($0.4 \text{ V} \approx 7 \times 60 \text{ mV}$): $J_e = (qn_i^2 D_e / N_{Ap} w_p) 10^7 = (1.6 \times 10^{-19} 10^{20} 4 \times 10^1 10^7) / (10^{17} 10^{-4}) = 0.64 \text{ mA/cm}^2$. Thus $J_h = 0.36 \text{ mA/cm}^2$, which in turn says $w_n = (qn_i^2 D_h / N_{Dn} J_h) 10^7 = (1.6 \times 10^{-19} 10^{20} 1.5 \times 10^1 10^7) / (10^{16} 3.6 \times 10^{-4}) = 0.67 \times 10^{-3} \text{ cm} = 6.7 \text{ } \mu\text{m}$. (Note: Depending on the approximations made, slightly different values can be obtained; all were accepted.)

Problem 2: Graded by Prof. Fonstad

- a) i) $J_{\text{Electron-B}} = q D_e dn' / dx = 1.6 \times 10^{-19} 4 \times 10^1 [(0 - 10^{13}) / (5 \times 10^{-4} - 3 \times 10^{-4})]$
 $= -3.2 \times 10^{-1} \text{ A/cm}^2$
- ii) $J_{\text{Hole-B}} = -q D_h dp' / dx = 1.6 \times 10^{-19} 1.5 \times 10^1 [(10^{14} - 5 \times 10^{14}) / (3 \times 10^{-4} - 2 \times 10^{-4})]$
 $= 9.6 \text{ A/cm}^2$
- iii) $I_3 = -A (J_{\text{Electron-B}} + J_{\text{Hole-B}}) = -10^{-4} [9.6 - (-0.32)] = 9.28 \times 10^{-4} \text{ A} \approx 0.93 \text{ mA}$
- iv) The excess minority population at the edge of a depletion region at a junction varies as n_i^2 / N_{Net} so if the excess population is 10 times lower in Region 3 than in Region 2, the doping level there must be 10 times larger than it is in Region 2. Thus, $n'(3^+) = 0.1 p'(3^-)$ implies $N_{A3} = 10 N_{D2} = 10^{18} \text{ cm}^{-3}$
- b) i) The excess minority population at the edge of a depletion region at a junction varies as n_i^2 / N_{Net} so if the doping is 10 times lower in Region 1 than in Region 2, the excess population there (at $x = 2^-$) will be 10 times larger than it is at $x = 2^+$. Thus, $N_{D2} = 10 N_{A1}$ implies $n'(2^-) = 10 p'(2^+) = 5 \times 10^{15} \text{ cm}^{-3}$.

[Note: This turns out to be high level injection, which is an oversight on our part because we did not intend to have you worry about high level injection. Fortunately no one even noticed, much less got hung up on it!]

- ii) The thermal equilibrium hole concentration in Region 2 is $10^{20} / 10^{17} = 10^3 \text{ cm}^{-3}$. The population at $x = 2^+$ has therefore increased to $5 \times 10^{14} \text{ cm}^{-3}$, a factor of 5×10^{11} , which is $e^{qV_{12}/KT}$. With this, and using the 60 mV rule, we estimate that V_{12} is $60 \log_{10} (5 \times 10^{11}) = 60 (11 + \log_{10} 5) \approx 60 \times 11.7 \approx 0.7 \text{ V}$.

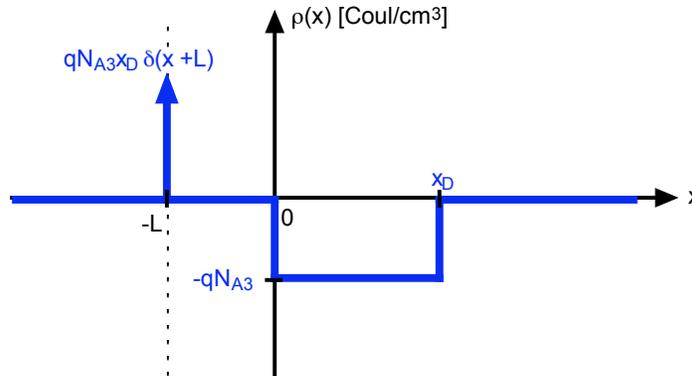
[Sorry about the $\log_{10} 5$ in this problem, but any good engineer should know $\log_{10} 5$, or $\log_{10} 2$, anyway. The first is 0.7, and the second is 0.3. Notice that they add to 1 because $5 \times 2 = 10$, so you really only need to know one of them.]

- c) i) Terminal 3 because Region 3 is the most heavily doped, and would function well as the emitter in a pnp BJT because $N_{A3} > N_{D2}$.
- ii) The profiles indicate there is little recombination in the base (≈ 0) so we can use $\beta_F = (1 - \delta_B) / (\delta_E + \delta_B) \approx 1 / \delta_E$. $\delta_E = D_h N_{A2} w_2 / D_e N_{A3} w_3 \approx 0.133$. If we use $\beta_F \approx 1 / \delta_E$, we find $\beta_F \approx 7.5$.

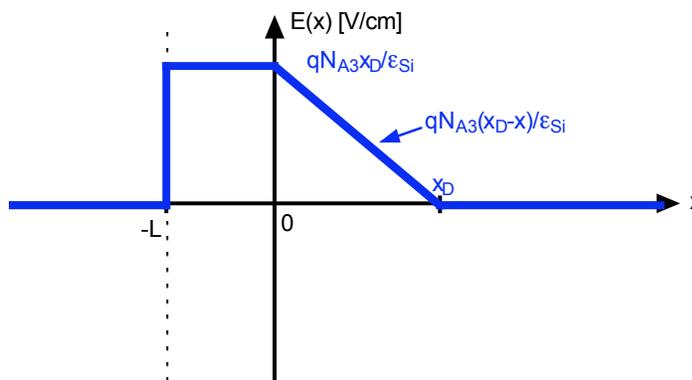
Problem 3: Graded by Prof. Antoniadis

a) $\phi_{n+} = 0.55 \text{ V}$ and $\phi_p = -0.42 \text{ V}$, so $\Delta\phi_{13} = 0.97 \text{ V}$.

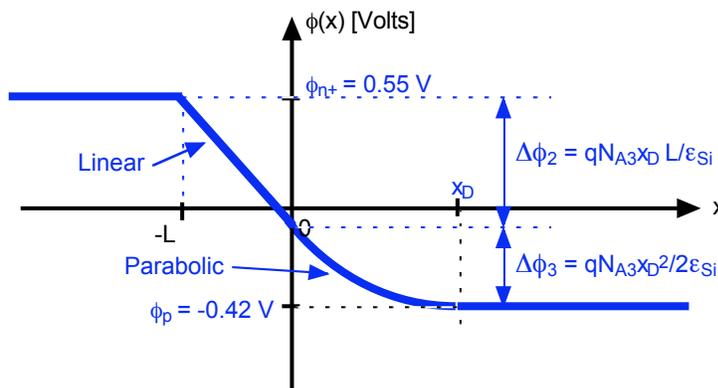
b)



c)



d)



e) We use the condition that the two voltage drops must add up to the built-in potential. The equation is: $\Delta\phi_{13} = qN_{A3}x_D L / \epsilon_{Si} + qN_{A3}x_D^2 / 2\epsilon_{Si}$

f) Since the dielectric constant is the same in all parts of this structure, the capacitance is simply that of a capacitor $(L+x_D)$ wide: $C_{dp}^* = \epsilon_{Si} / (L+x_D)$.

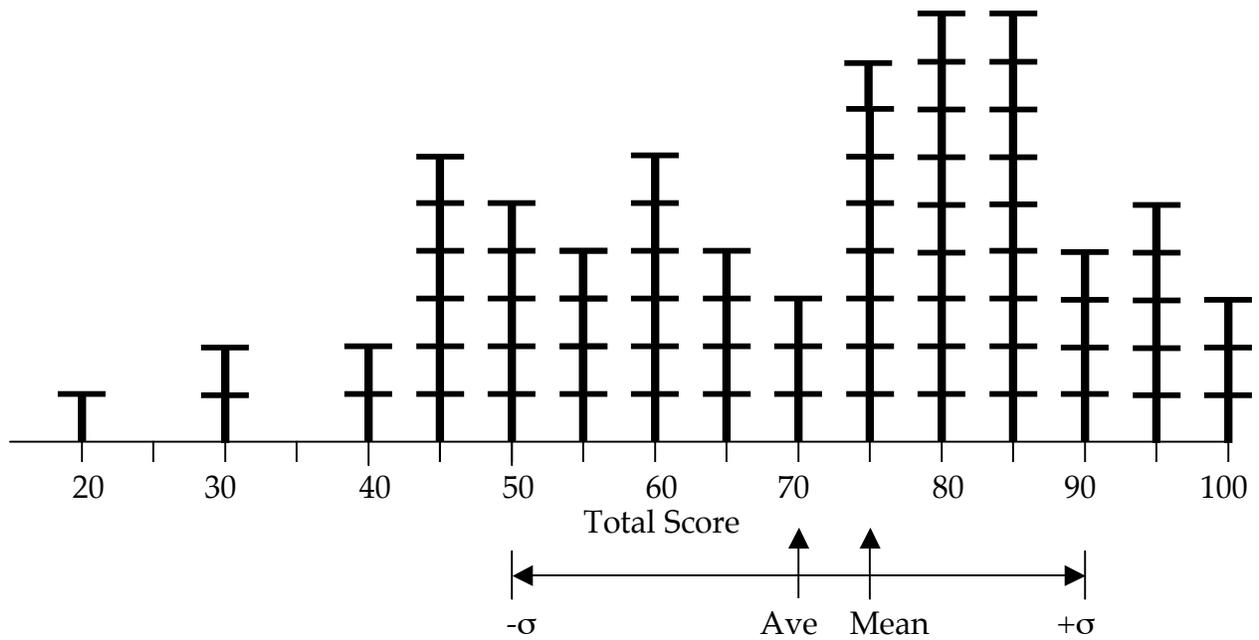
Exam Statistics

Average/Standard deviation:	Problem 1	26.6	6.2
	Problem 2	23.6	7.9
	<u>Problem 3</u>	<u>19.7</u>	<u>8.6</u>
	Total	69.9	19.0

Class median: 74

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