ANSWERS: Semiconductor Physics Problems 2019

Page and figure numbers refer to Semiconductor Devices – Physics and Technology, 3rd edition, by SM Sze and M-K Lee

1. (a) $5 \cdot 10^{10}$ cm^{-3}
   (b) No, most probably not. The lowest possible number of impurities exceeds the intrinsic carrier concentration by a factor 5, so most probably the mix of impurities contributes non-negligibly to the carrier concentrations.

2. (a) F
   (b) B

3. The answers were computed using N_C and N_V (at 300K) from appendix G, even though these are really temperature dependent. A more careful numerical/graphical solution will yield values which are 10-20 K higher than those listed here.

   Donor/acceptor ionization energies can be found in figure 20 (p 35) [fig 24 p 38 in the second edition].

   (a) 72 (72.4) K
   (b) n-type sample: 1160 (1156) K, p-type sample 820 K
   (c) (used n_i from appendix G) n-type: $9.3 \cdot 10^3$ cm^{-3}, p-type: $9.3 \cdot 10^4$ cm^{-3}
   (d) n-type: $E_F = E_V + 0.914$ eV, p-type: $E_F = E_V + 0.263$ eV, mixed: $E_F = E_V + 0.911$ eV

4. (a) plotting $\log(n)$ vs $1/T$ allows for extracting E_g and/or E_d/E_a from the slopes. It doesn't even have to be n (or p) of the y-axis, only something (like conductivity) proportional to it.
   (b) If the relevant slope is measured to be -244.6 K (you may get something slightly different), the donor binding energy comes to 42 meV (slope corresponds to $-(E_C - E_D)/2k$. From fig 20 p. 35 in Sze this seems to correspond best to Sb or P.

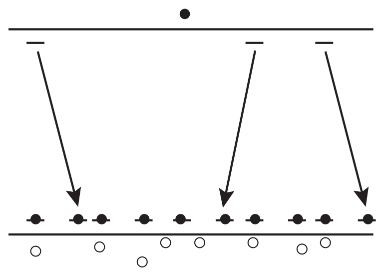
5.

$$p = N_V e^{(-(E_F - E_V)/kT)} = N_A^-$$

$$F(E_A) = \frac{1}{1 + e^{(E_A - E_F)/kT}}$$

Choosing for instance N_A^-/N_A to be 0.8 (80%) as a starting guess, yields a value (eqn 1) for E_F ($E_F = E_V + 0.2096$ eV). Plugging this value into the Fermi distribution function and evaluating the probability for occupation at E_A returns 0.9983, meaning that 99.83 % are ionized.

The iteration converges to 99,79% of the acceptors ionized, which corresponds to a Fermi level 0.2038 eV above E_V. Calculating E_F under the assumption that all acceptors are ionized, so that $p = N_V e^{-(E_F - E_V)/kT} = N_A$, yields $E_F = E_V + 0.2038$ eV. Plugging this into the Fermi distribution yields 0.9979. In conclusion we can safely approximate the acceptors to be completely ionized.



6. In a and b (Si samples) n_i is small enough that the effect on the carrier concentrations under these particular doping concentrations is negligible, while in c and d (Ge sample) n_i is large due to the smaller bandgap. In sample c, the correction from considering the full expression is small, but in sample d it is larger.

7. $N_D = 1.67 \cdot 10^{17}$ cm^{-3}.

8. **HAND-IN**

9. Using effective densities of states from appendix G in Sze, we find:

   For Si: $E_C - E_F$ is about 5.6$\times kT$ and 3.35$\times kT$, respectively. $n = N_C e^{(E_F - E_C)/kT}$ was derived under the assumption that $E_C - E_F$ was at least $3kT$ (see Sze). Fermi level position is probably still a fairly relevant value even at the higher doping density considered here, but an even higher doping would make matters worse.

   For GaAs: $E_C - E_F$ is about 1.55$\times kT$ and $-0.75 \times kT$, respectively. The approximation cannot be said to be valid, and for the higher doping E_F even turns out to be above E_C.

   The reason $E_C - E_F$ for Si and GaAs are so different given a certain doping is that the lower electron effective mass of GaAs reduces the effective density of states which forces the Fermi level upwards for an n-type sample. In addition, modern devices, semiconductors are often designed into thin layers or narrow stripes, which changes (reduces) the density of states making it even more probable that the semiconductor is degenerate.

10. b, d are true

11. $v_{th} = 1.4 \cdot 10^5$ m/s and the drift velocity $v_p = 20$ cm/s.

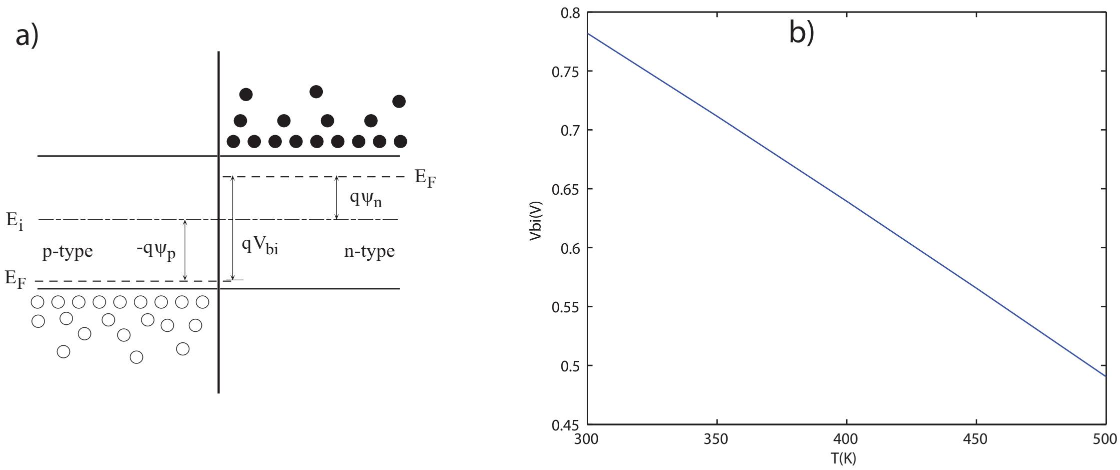
12. $n = 10^{15}$ cm^{-3} and $p = 10^{11}$ cm^{-3}. The majority carrier concentration is barely affected by the extra generation, while the minority charge carrier concentration is increased - that is, low-level injection.

13. convince yourself ...

14. (a) E_F varies relative to the band edges which gives a variation in n and p.
    (b) Variation in band edge is realted to variation in the potential, $-q\Delta\Psi = \Delta E_C$
    (c) the electric field is given by the variation in potential; $\mathscr{E} = -d\Psi/dx$
    (d) $J_n = J_p = 0$

15. Consider a pn-junction with impurity concentrations as indicated in the figure above. Compute
    (a) The minority carrier concentration in region 1 is $9.8 \cdot 10^2$ cm^{-3}
    (b) The minority carrier concentration in region 2 is $1.9 \cdot 10^4$ cm^{-3}
    (using n_i from appendix G)
    To compute V_{bi} alternative c should be used.

16. (a) see figure
    (b) see figure
    (c) -



    (d) $W = 0.975\ \mu$m, $\mathscr{E}_{max} = 1.46 \cdot 10^6$ V/m

17. **HAND-IN**

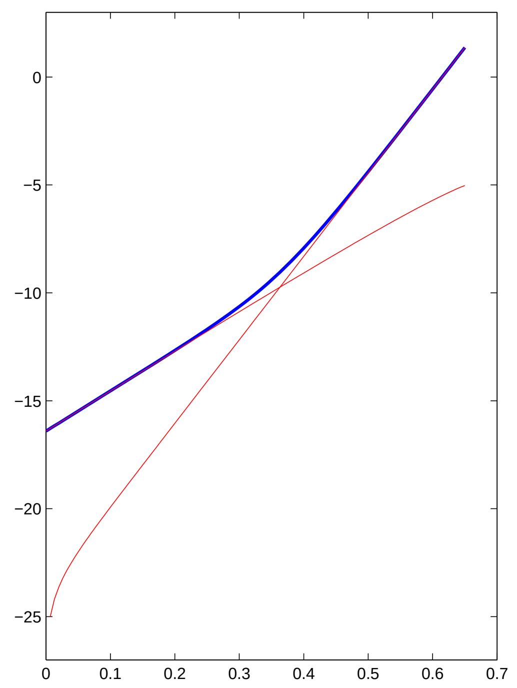
18. **HAND-IN**

19. **HAND-IN**

20. From figure 7 on page 51 we can find doping densities - we picked $N_A = 10^{16}$ cm^{-3} and $N_D = 3 \cdot 10^{16}$ cm^{-3}. From fig 3 on page 47 we approximated the diffusivities as $D_n = 30$ cm^2/Vs and $D_p = 10$ cm^2/Vs

    (a) $V_{bi} = 0.745$ V
    (b) $n_p = 9.1 \cdot 10^{13}$ cm^{-3} and $p_n = 3.0 \cdot 10^{13}$ cm^{-3}
    (c) Qualitatively similar to fig 15 a on page 102 in Sze; that is $J_p(x_n) > J_n(-x_p)$. Thus, the point where the currents are of equal magnitude occur on the n-side.
    (d) $x_n + 0.87$ μm.

21. (a) x-axis: voltage in V. y-axis: $\ln I$. The figure is plotted on a logarithmic scale so that it is possible to estimate the ideality factor. It is 1 for high voltages and 2 for lower voltages, as expected (do you agree?). The blue line is the total current (diffusion and recombination contribution added).



22. (a) 0.90 μm
    (b) $n_p(0) = 1.17 \cdot 10^{11}$ cm^{-3}

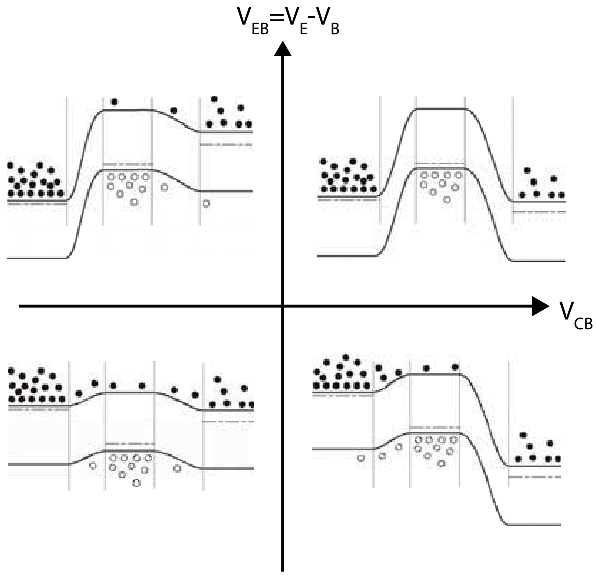
23. HAND-IN

24. HAND-IN

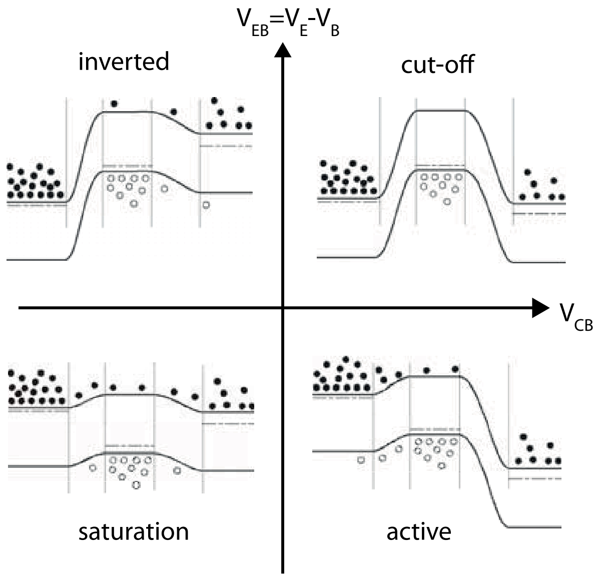
25. HAND-IN

26. $V_{EB} = -0.165$ V and $I_{CBO} = 3.54 \cdot 10^{-14}$ A.

27. Band diagrams for an npn-transistor under the given biasing conditions. As an extra exercise I left the labels of the modes out. Try to label them yourself (active, saturated, inverted and cut-off). Answer on next page.

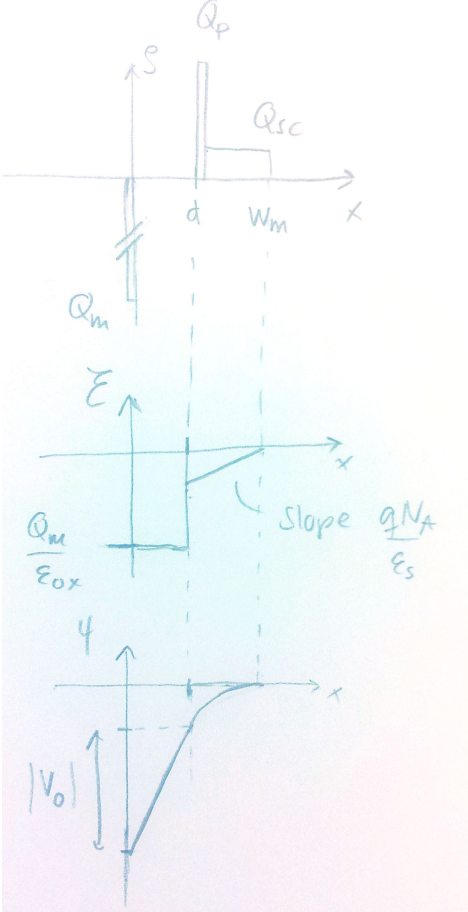


Labelled band diagrams



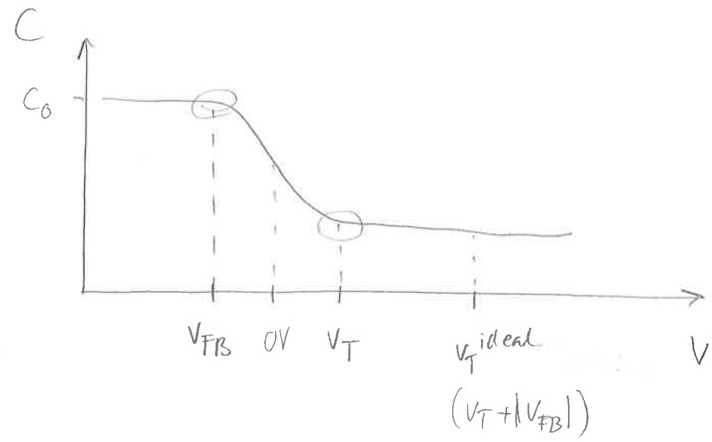
28. The circuit is an inverter: for $v_{in} = 1$ V $v_{out} = 10$ V and for $v_{in} = 2$ V $v_{out} = 5$ V. ”Low in” gives ”high out” and opposite.

29. inverted n-type

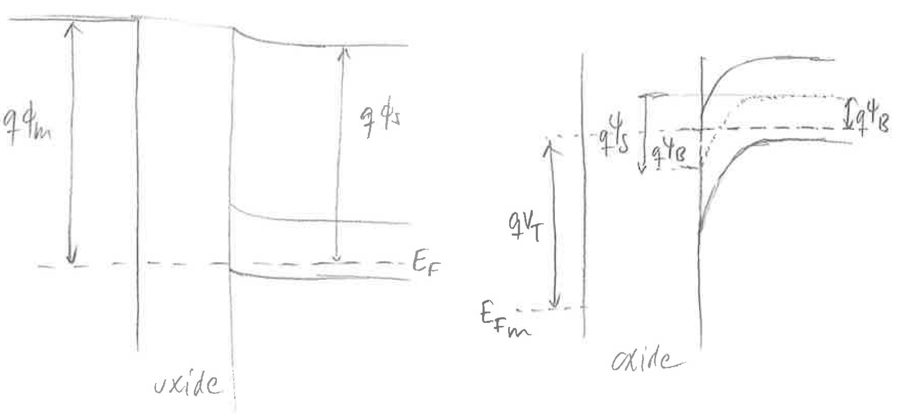


30.

31. HAND-IN



32. (a) $\phi_{gate} - \phi_s = -(\frac{E_g}{2q} + \Psi_B) = -0.978$ V
    (b) $V_T = 0.83$ V (less than V_T^{ideal}).
    (c) See above.
    (d) $C_{max} = 1.73 \cdot 10^{-7}$ F/cm^2 and $C_{min} = 6.36 \cdot 10^{-8}$ F/cm^2 (for high frequency).



33. (a) Band biagrams above (thermal equilibrium to the left, onset of inversion to the right). $V_T = 2.00$ V
    (b) $I_D = I_{Dsat} = 2.78 \cdot 10^{-6}$ A
    (c) $I_D = 1.46 \cdot 10^{-5}$ A

34. (a) $V_T = 1.54$ V
    (b) When $V_D = V_G$, the device is in saturation. $\sqrt{I_D}$ is then linear in $V_D(= V_G)$, and is ideally 0 when $V_D = V_G < V_T$.

35. (a) No, ideally it is not conducting as it is gated below V_T.
    (b) An analytical solution is difficult - some numerical trial-and error gives that the doping level needs to be reduced to $N_A \approx 3.2 \cdot 10^{16}$ cm^{-3}.
    (c) Numerical testing gives a new oxide layer thickness of $d \approx 9.7$ nm

36. Truth table:

V_A	V_B	V_{OUT}
0	0	1
0	1	1
1	0	1
1	1	0

    The circuit performs a NAND operation.

37. HAND-IN

38. HAND-IN

39. The voltage drop over the Schottky diode (metal-semiconductor junction) needs to be 0.298 V, while the pn-junction requires 0.58 V in order for the same current to flow.

40. (a) $D_{it} = 3 \cdot 10^3$ states/(cm^2·eV). Sze gets $D_{it} = 4 \cdot 10^3$ states/(cm^2·eV) on page 142 (e-book!) - don't know how he does that, and anyway it is the same order of magnitude.
    (b) Assuming that E_F coincides with the neutral level, we find $qV_{bi} = 0.7$ eV and a depletion region width $W = 3 \cdot 10^{-6}$ cm. Next we find that the Fermi level can be shifted by 0.1 eV from the neutral level in order to have the charge at the interface being equal in magnitude to the charge in the depletion region.