Problems

1. An abrupt silicon p-n junction ($N_a = 10^{16}$ cm^{-3} and $N_d = 4 \times 10^{16}$ cm^{-3}) is biased with $V_a = -3$ V. Calculate the built-in potential, the depletion layer width and the maximum electric field of the junction.

2. An abrupt silicon p-n junction consists of a *p*-type region containing 10^{16} cm^{-3} acceptors and an *n*-type region containing also 10^{16} cm^{-3} acceptors in addition to 10^{17} cm^{-3} donors.

   a) Calculate the thermal equilibrium density of electrons and holes in the *p*-type region as well as both densities in the *n*-type region.

   b) Calculate the built-in potential of the p-n junction.

   c) Calculate the built-in potential of the p-n junction at 100°C.

3. Consider an abrupt silicon p-n junction with a built-in potential of 0.62 V.

   a) What is the potential across the depletion region at an applied voltage, V_a, of 0, 0.5 and -2 Volt?

   b) If the depletion layer is 1 micrometer at $V_a = 0$ Volt, find the maximum electric field in the depletion region.

   c) Assuming that the net doping density $|N_d - N_a|$ is the same in the *n*-type and *p*-type region of the diode, carefully sketch the electric field and the potential as a function of position throughout the depletion region. Add numeric values wherever possible.

   d) Calculate the doping density in the *n*-type and *p*-type region.

4. An abrupt silicon ($n_i = 10^{10}$ cm^{-3}) p-n junction consists of a *p*-type region containing 10^{16} cm^{-3} acceptors and an *n*-type region containing 5×10^{16} cm^{-3} donors.

   a) Calculate the built-in potential of this p-n junction.

   b) Calculate the total width of the depletion region if the applied voltage V_a equals 0, 0.5 and -2.5 V.

   c) Calculate maximum electric field in the depletion region at 0, 0.5 and -2.5 V.

   d) Calculate the potential across the depletion region in the *n*-type semiconductor at 0, 0.5 and -2.5 V.

5. Consider an abrupt p-n diode in thermal equilibrium with as many donors in the *n*-type region as acceptors in the *p*-type region and a maximum electric field of -13 kV/cm and a total depletion layer width of 1 μm. (assume $\varepsilon_s / \varepsilon_0 = 12$)

   a) What is the applied voltage, V_a?

   b) What is the built-in potential of the diode?

   c) What is the donor density in the *n*-type region and the acceptor density in the *p*-type region?

d) What is the intrinsic carrier density of the semiconductor if the temperature is 300 K ?

6. A silicon ($n_i = 10^{10}$ cm^{-3}) p-n diode with $N_a = 10^{18}$ cm^{-3} has a capacitance of 10^{-8} F/cm^2 at an applied voltage of 0.5 V. Find the donor density.

7. A silicon ($n_i = 10^{10}$ cm^{-3}) p-n diode has a maximum electric field of -10^6 V/cm and a depletion layer width of 1 μm. The acceptor density in the p-type region is four times larger than the donor density in the n-type region. Calculate both doping densities.

8. Consider a symmetric silicon p-n diode ($N_a = N_d$)

   a) Calculate the built-in potential if $N_a = 10^{13}$, 10^{15} and 10^{17} cm^{-3}. Also, calculate the doping densities corresponding to a built-in potential of 0.7 V.

   b) For the same as in part a), calculate the total depletion layer widths, the capacitance per unit area and the maximum electric field in thermal equilibrium.

   c) Repeat part a) and b) with $N_a = 3\ N_d$.

9. A one-sided silicon diode has a breakdown voltage, $|V_{br}|$, of 1000 V for which the maximum electric field at breakdown is 100 kV/cm. What is the maximum possible doping density in the low doped region, the built-in potential, the depletion layer width and the capacitance per unit area? Assume that bulk potential of the highly doped region is $E_g/2$ (= 0.56 V).

10. A silicon p-n junction ($N_a = 10^{16}$ cm^{-3} and $N_d = 4 \times 10^{16}$ cm^{-3}) is biased with $V_a = 0.6$ V. Calculate the ideal diode current using $w_n' = 1$ μm and $w_p' = 100$ μm. Use $\mu_n = 1000$ cm^2/V-s and $\mu_p = 300$ cm^2/V-s. The minority carrier lifetime is 100 μs and the diode area is 100 μm by 100 μm.

11. Derive equation (4.4.28) from (4.4.14).

12. Calculate the relative error when using the "short diode" approximation if $L_n = 2\ w_p'$ and $L_p = 2\ w_n'$.

13. A silicon p-n junction ($N_a = 10^{15}$ cm^{-3}, $w_p = 1$ μm and $N_d = 4 \times 10^{16}$ cm^{-3}, $w_n = 1$ μm) is biased with $V_a = 0.5$ V. Use $\mu_n = 1000$ cm^2/V-s and $\mu_p = 300$ cm^2/V-s. The minority carrier lifetime is 10 μs and the diode area is 100 μm by 100 μm.

   a) Calculate the built-in potential of the diode.

   b) Calculate the depletion layer widths, x_n and x_p, and the widths of the quasi-neutral regions.

   c) Compare the width of the quasi-neutral regions with the minority-carrier diffusion-lengths and decide whether to use the "long" or "short" diode approximation. Calculate the current through the diode.

   d) Compare the result of part c) with the current obtained by using the general solution

(equation 4.4.14)

e) Using the approximation chosen in part c) calculate the ratio of the electron current to the hole current traversing the depletion region.

14. An abrupt silicon p-n diode consists of a *p*-type region containing 10^{18} cm^{-3} acceptors and an *n*-type region containing 10^{15} cm^{-3} donors.

a) Calculate the breakdown field in the *n*-type region.

b) Using the breakdown field from part a), calculate the breakdown voltage of the diode.

c) What is the depletion layer width at breakdown?

d) Discuss edge effects and specify the minimum junction depth needed to avoid these effects.

15. A 1 cm^2 solar cell consists of a *p*-type region containing 10^{18} cm^{-3} acceptors and an *n*-type region containing 10^{15} cm^{-3} donors. $w_p' = 0.1$ µm and $w_n >> L_p$. Use $\mu_n = 1000$ cm^2/V-s and $\mu_p = 300$ cm^2/V-s. . The minority carrier lifetime is 10 µs . The diode is illuminated with sun light, yielding a photocurrent density of 30 mA/cm^2.

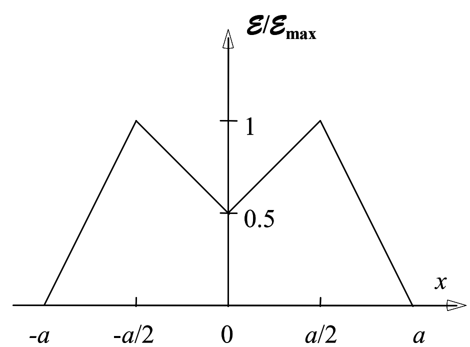
a) Calculate the open circuit voltage and short-circuit current of the solar cell.

b) Calculate the maximum power generated by the call and the corresponding voltage and current.

c) Calculate the fill factor of the solar cell.

d) Calculate the fill factor for the same cell when a concentrator illuminates it so that the photocurrent density equals 300 A/cm^2.

16. A semiconductor device made of silicon has, under thermal equilibrium, an M-shaped electric field distribution as shown in the figure below.



a) Find N_d - N_a between $x = -a$ and $x = a$, as a function of $\mathcal{E}_{max}$

b) Find the total potential across the semiconductor as a function of $\mathcal{E}_{max}$ with $a = 0.1$ µm

c) Find $\mathcal{E}_{max}$ and the built-in voltage ϕ_i

d) Plot N_d - N_a for $-a \leq x \leq a$ and indicate numeric values. Specify whether the different regions are *p*–type or *n*-type.

17. Design an abrupt silicon p-n diode with a capacitance per unit area of 10 nF/cm^2 in thermal equilibrium and a maximum electric field of 10^5 V/cm at a reverse bias of 10 Volt. Provide values of the acceptor and donor density, the built-in potential and the depletion layer width in thermal equilibrium and at a reverse bias of 10 Volt.

18. A silicon p-n junction consists of a half-sphere with one-micron radius and a doping density of 10^{18} cm^{-3} embedded in an *n*-type substrate with a donor density of 10^{16} cm^{-3}. Breakdown occurs in the diode when the maximum field reaches 6 x 10^5 V/cm. Calculate the breakdown voltage. Justify any assumptions you make.

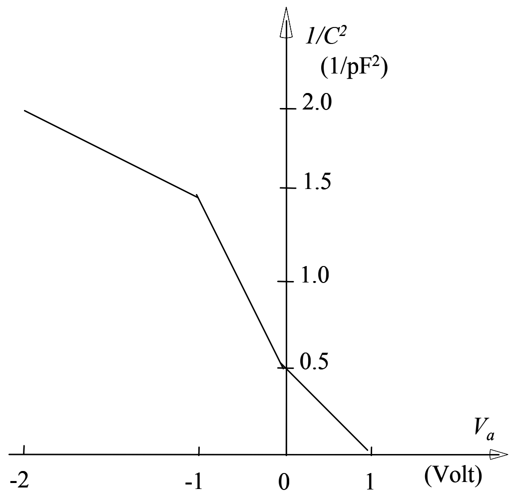
19. Calculate the built-in voltage for a silicon p-n junction with $N_a = N_d = 10^{15}$ cm^{-3} at $T = 500$ K. Do not assume the electron and hole concentration to equal the donor or acceptor concentration.

20. Derive the minority electron density in a silicon p-n junction at the edge of the depletion region as a function of the acceptor density and the applied voltage. State the approximations made. Calculate the minority electron density for $N_a = 10^{17}$ cm^{-3}, $N_d = 10^{16}$ cm^{-3} and $V_a = -2$ V.

21. An abrupt silicon ($n_i = 10^{10}$ cm^{-3}, $\varepsilon_s/\varepsilon_0 = 11.9$) p-n diode has a maximum electric field of -10^6 V/cm and a depletion layer width of 10 μm. The acceptor density in the p-type region is three times larger than the donor density in the n-type region. Calculate both doping densities.

22. A one-sided abrupt silicon ($n_i = 10^{10}$ cm^{-3}, $\varepsilon_s/\varepsilon_0 = 11.9$) p-n junction with $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3} is biased with $V_a = 0.7$ V. Calculate the ideal diode current using the following parameters: $w_p' = w_n' = 100$ μm, $\mu_n = 500$ cm^2/V-s and $\mu_p = 300$ cm^2/V-s. The minority carrier lifetime is 1 μs and the diode area is 100 μm by 100 μm. Use either the "long" or "short" diode equation and justify your choice.

23. A capacitance measurement of a one sided p$^+$-n diode resulted in the following plot of $1/C^2$ versus the applied voltage.



Calculate and plot the doping profile N_d as a function of the distance from the metallurgical interface. The diode are is 10^{-4} cm^2 and the relative dielectric constant of the semiconductor is 12. If the electron and hole masses equal the free electron mass, m_0, what is the bandgap of the semiconductor?

24. A "long" abrupt p-n diode consists of a *p*-type region with a four times higher resistivity than the n-type region, while the depletion layer width in the *p*-type region is twice that in the *n*-type region. What is the ratio of the maximum electron current to the maximum hole current? Assume the minority carrier lifetime to be the same in both regions

25. For a silicon p-n diode find the maximum built-in voltage at 300K, assuming non-degenerate material. Repeat at 300C.

26. An n^+-n-p^+ diode has the following field distribution:

    a) Calculate the voltage applied to the diode
    b) Plot then charge distribution throughout the depletion region at that bias voltage
    c) Calculate the donor density in the middle region.

27. A one-sided p+-n diode has an n-type region width w_n which is much larger than the hole diffusion length L_p. Derive an expression for the current $I(V)$ through the diode, taking into account the modulation of the depletion region due to the applied voltage. Ignore the injection of electrons into the p-type region.

28. An abrupt p-n diode consists of a p-type region containing 10^{16} cm^{-3} shallow acceptors and an n-type region containing also 10^{16} cm^{-3} shallow acceptors in addition to 10^{17} cm^{-3} shallow donors.

    a) Calculate the thermal equilibrium density of electrons and holes in the p-type region as well as both densities in the n-type region.
    b) Calculate the built-in potential of the p-n diode.
    c) Calculate the built-in potential of the p-n diode at 100^{o}C

29. For a p-n diode with a built-in potential of 0.62 V,

    a) What is the potential across the depletion region at an applied voltage, V_a, of 0, 0.5, and -2 Volt?

b) If the depletion layer is 1 micron at $V_a = 0$ Volt, find the maximum electric field in the depletion region.
c) Assuming that the net doping density, $|N_d - N_a|$ is the same in the *n*-type and *p*-type region of the diode, carefully sketch the electric field and the potential as a function of position throughout the depletion region. Add numeric values whenever possible.

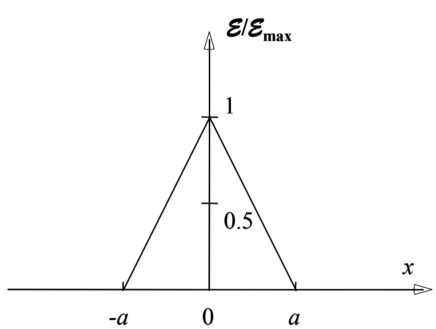
30. Consider a one-sided silicon p$^+$-n junction with $V_a = 0.6$ Volt, $N_d = 10^{15}$ cm^{-3}, $\tau_n = \tau_p = 10$ μs
    a) Calculate the electron and hole density at the edge of the n-type quasi-neutrral region
    b) Calculate the hole current density at the edge of the n-type quasi-neutral region and 10 microns away from that edge in to quasi-neutral region. Assume the quasi-neutral region to be "long".

31. An abrupt p-n diode has a built-in potential of 0.75 Volt and a depletion layer width of 1 micron at a forward bias of 0.5 Volt. What is the width of the depletion layer at a reverse bias voltage of 1 Volt?

32. An abrupt p-n diode has a built-in potential of 0.7 V and an *n*-type region doped with 10^{16} cm^{-3} shallow donors. Calculate the acceptor density, N_a, in the *p*-type region, the depletion layer width in both regions, x_n and x_p, and the maximum electric field, $\mathcal{E}_{max}$, if the diode is in thermal equilibrium.

33. Consider an abrupt silicon p-i-n diode with $N_a = N_d = 10^{17}$ cm^{-3} and a 2 micron wide intrinsic region. $V_a = 0$ Volt.
    a) Calculate the electric field using the full depletion approximation
    b) Draw the corresponding energy band diagram
    c) Calculate $n(x)$ and $p(x)$ in the intrinsic material from $n = n_i \exp[(E_F - E_i)/kT]$ and $p = n_i \exp[(E_i - E_F)/kT]$
    d) Calculate $J_n(x)$ in the intrinsic material
    e) Does the drift current equal the diffusion current in the intrinsic material? Why? Is the full depletion approximation valid? Why?

34. The field distribution of an abrupt silicon p-n diode is shown below.



The electron density at $x = -a = -0.1$ μm equals 10^{17} cm^{-3}. Calculate the electron density at $x = a = 0.1$ μm. The maximum electric field equals $\mathcal{E}_{max} = 1.5 \times 10^5$ V/cm. Note that the diode is not in thermal equilibrium.

35. An abrupt silicon p-n diode is uniformly doped with a donor density, $N_d = 10^{17}$ cm^{-3}, in the *n*-type and an unknown acceptor density in the *p*-type region. The depletion layer width in the n-type region is three times the depletion layer width in the p-type region and the maximum electric field in the junction is 10^5 V/cm. Find the acceptor density, the built-in potential, the applied voltage and the corresponding junction capacitance per unit area.

36. A silicon p-n with a saturation current of 10^{-10} A is used as a solar cell. The diode is illuminated with sunlight, yielding a photocurrent of 1 mA. Find the maximum power, which can be generated by this diode. Calculate the corresponding voltage and current.

37. Derive equation (4.6.3).