NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
TERM 1

H3 – Semiconductor Physics & Devices

TUTORIAL 7 PN Junction in Equilibrium

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1. The donor and acceptor doping densities of a Si p-n junction are $N_d = 10^{16}$ cm^{-3} and $N_a = 10^{15}$ cm^{-3}, respectively. Assume room temperature (300 K), $n_i = 1.5\times10^{10}$ cm^{-3} and $\varepsilon_r = 11.8$. Calculate the equilibrium space charge width and the peak electric field in the p-n junction. **[Ans: 0.956 μm and –1.33×10^4 V/cm]**

2. A Si p-n junction has donor and acceptor doping concentrations, N_d and N_a of 10^{16} cm^{-3} and 10^{18} cm^{-3}, respectively. Assume kT = 0.026 eV at 300 K, $n_i = 1.5\times10^{10}$ cm^{-3} and $\varepsilon_r = 11.8$. Calculate under thermal equilibrium conditions, the followings:

   a) Fermi energy level positions in the n- and p-side. Draw an equilibrium energy band diagram and obtain the contact potential from the diagram.
   b) Contact potential V_0 (compare it to that obtained in part (a))
   c) Depletion width W_0
   d) Penetration depth into the n-side and p-side.
   e) Peak electric field $\xi_{0,\,max}$ at the junction.
   f) Space charge in each side of the depletion region, given a cross-sectional area of 10^{-4} cm^2.

   Comment on the depletion width and penetration depths obtained in relation to the doping concentration on each side.

   [Ans: (a) $E_{ip} - E_{Fp}$ = 0.468 eV, $E_{Fn} - E_{in}$ = 0.349 eV, (b) 0.817 V, (c) 0.328 μm, (d) $x_{p0} = 3.25\times10^{-3}$ μm, x_{n0} = 0.325 μm, (e) –5×10^4 V/cm, (f) 5.2×10^{-12} C]

3. Show mathematically that the Fermi-levels on the n-side and p-side of a p-n junction at thermal equilibrium form a single horizontal line in the energy band diagram.

4. Consider a uniformly doped Si p-n junction at 300 K. At thermal equilibrium, it is designed such that 10% of the total depletion width will occur at the p region. You are given that the equilibrium built in potential is 0.8 V. Assume that $\varepsilon_r = 11.8$ and the intrinsic concentration $n_i = 1.5 \times 10^{10}$ /cm^3 for Si. Determine the doping concentrations N_a and N_d of both sides of the junction and the total depletion width.

   [Ans: $N_a = 2.29\times10^{17}$ cm^{-3}, $N_d = 2.55\times10^{16}$ cm^{-3}, W = 0.213 μm]

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TUTORIAL 8 PN Junction Under Bias

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1. Calculate the forward bias V_F required to achieve a current of 15 mA in an ideal p-n junction at 300 K of an ideal p-n junction diode at 300K if the reverse saturation current I_o is (a) 5 μA and (b) 8 pA.

   [Ans: 0.2 V, 0.53 V]

2. An abrupt Si p-n junction has donor and acceptor doping concentrations N_d and N_a of 10^{16} cm^{-3} and 10^{18} cm^{-3}, respectively. Assume kT = 0.026 eV at 300 K, $n_i = 1.5\times10^{10}$ cm^{-3} and $\varepsilon_r = 11.8$. Calculate the following parameters at (i) a FB of 0.65 V and (ii) a RB of 2 V.

   a) Contact or junction potential. Draw the band diagrams, indicating clearly the extent of band bending.
   b) Depletion width W.
   c) Penetration depth into the n-side and p-side.
   d) Peak electric field ξ_{max}.
   e) Space charge stored in each side of the depletion region, given a cross-sectional area of 10^{-4} cm^2.

   [Ans: (a) V_c = 0.167 V, V_c = 2.817 V, (b) 0.148 μm, 0.610 μm, (c) 1.47×10^{-3} μm, 0.147 μm, 6.04 ×10^{-3} μm, 0.604 μm, (d) –2.251×10^{4} V/cm, –9.25×10^{4} V/cm, (e) 2.35 pC, 9.66 pC]

3. Consider a Si p-n junction with donor and acceptor doping concentrations N_d and N_a of 10^{15} cm^{-3} and 10^{18} cm^{-3}, respectively. A forward bias of 0.52 V is applied to the p-n junction. Calculate the minority-carrier concentrations at the depletion-layer edges. A very weak electric field exists in the quasi-neutral regions of the semiconductor (outside the depletion region). Estimate the ratio of the majority carrier to minority carrier drift currents at the depletion layer edge and deep inside the n-region. Assume that the diode is at room temperature (300 K), μ_n = 1350 cm^2/V-s, μ_p = 450 cm^2/V-s and $n_i = 1.5\times10^{10}$ cm^{-3}. Comment on the answers.

   [Ans: 10^{14} cm^{-3}, 10^{11} cm^{-3}, 30, 1.34×10^{10}]

4. An ideal Si p-n junction diode is fabricated with 1 Ω-cm p-type and 0.2 Ω-cm n-type materials in which the minority carrier lifetimes are $\tau_n = 10^{-6}$ s and $\tau_p = 10^{-8}$ s, respectively. The diode is forward biased at 0.55 V.

   a) Calculate the donor concentration of the n-type material and the acceptor concentration of the p-type material.
   b) Calculate the minority carrier diffusion lengths.
   c) Calculate the density of minority carriers at both edges of the space charge region.

d) Sketch the majority and minority carrier distributions as functions of distance from the junction indicating the minority carrier diffusion lengths on the distance axis.
e) Sketch the majority and minority carrier currents outside the space charge region as functions of distance from the junction.
f) Calculate the location of the plane at which the majority carrier and minority carrier currents are equal in magnitude.

Assume that T = 300 K, kT = 0.026 eV, and for Si, μ_n = 0.145 m^2/V-s, μ_p = 0.045 m^2/V-s and $n_i = 1.5\times10^{10} cm^{-3}$.

[Ans: (a) 2.16×10^{22} m^{-3}, 1.39×10^{22} m^{-3}, (b) 6.14×10^{-5} m, 3.42×10^{-6} m, (c) 1.6×10^{19} m^{-3}, 2.49×10^{19} m^{-3}, (f) 1.53×10^{-6} m from the edge at the n-side]

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TUTORIAL 9 PN Junction Under Bias, Junction Capacitance

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1. A Si p-n junction diode has the following parameters at 300 K

   $D_n = 25\ cm^2/s$ $D_p = 10\ cm^2/s$ $\tau_n = \tau_p = 0.5\ \mu s$ $n_i = 1.5\times10^{10}\ /cm^3$

   Given that the electron diffusion current density at the depletion region edge is 20 A/cm^2 and the hole diffusion current density at the depletion region edge is 5 A/cm^2 at a forward bias of 0.65 V, determine the doping densities of the p and the n regions.

   [Ans: $N_a = 10^{15}\ /cm^3$ and $N_d = 2.5\times10^{15}\ /cm^3$]

2. Consider a reverse-biased p-n junction of cross-sectional area A. Determine the thermal generation rates of minority carriers within the volumes of L_nA and L_pA, where L_n and L_p are the minority electron and hole diffusion length respectively (viz., determine the generation rates per second over a diffusion length from each side of the depletion region in a p-n junction). Show that the sum of the resultant current flows due to the thermal generation is equal to the reverse saturation current in a p-n junction. Comment on your results.
   Hint: The thermal generation rate g in a doped semiconductor is given by $\alpha_r n_o p_o$ $cm^{-3}s^{-1}$. The minority carrier lifetime (τ_n or τ_p) is given by $(\ \alpha_r(n_o + p_o)\ )^{-1}$.

3. An abrupt Si p-n junction has donor and acceptor doping concentrations N_d and N_a of $10^{16}\ cm^{-3}$ and $10^{18}\ cm^{-3}$, respectively. Assume kT = 0.026 eV at 300 K, $n_i = 1.5\times10^{10}\ cm^{-3}$ and $\varepsilon_r = 11.8$. Given that the junction has an area of $10^{-4}\ cm^2$, calculate the junction capacitance at (i) zero bias (ii) a FB of 0.65 V and (ii) a RB of 2 V.

   [Ans: 3.18 pF, 7 pF, 1.7 pF]

4. Room temperature (300 K) measurements on an abrupt Si p^+-n junction diode yield the following results: With a reverse bias of 4.2 V, the junction capacitance is 20 pF. When the reverse bias is changed to 0.43 V, the junction capacitance is 40 pF. If $n_i = 1.5\times10^{10}\ cm^{-3}$, $\varepsilon_r = 11.8$, and the diode area is $2\times10^{-3}\ cm^2$, determine the contact potential V_o and the doping density of the n-side N_d.

   [Ans: 0.827 V, $6\times10^{15}\ cm^{-3}$]

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TUTORIAL 10 PN Junction and Storage Capacitances, Schottky Contacts

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1. Show that a plot of $1/C_j^2$ vs. V, where V is the applied reverse bias and C_j is the junction capacitance, is a straight line for an abrupt and uniformly doped one-sided junction. What parameters could be extracted from such a plot and how?

2. Consider a silicon p^+-n junction with $N_d = 10^{16}$ cm^{-3}. The area of the diode is 10^{-4} cm^2. Assume kT = 0.026 eV at 300 K, $n_i = 1.5\times10^{10}$ cm^{-3} and $\varepsilon_r = 11.8$. Holes in the n-region have a lifetime of 0.5 μs and a diffusion coefficient of 10 cm^2/s. Calculate the storage capacitance of the p^+-n junction at a forward bias of 0.65 V. **[Ans: 2.23 nF]**

3. An ideal Schottky contact is formed on n-type Si having a donor concentration of 10^{17} cm^{-3}. The bandgap of Si at 300 K is 1.1 eV. The metal work function $q\phi_m$ is 5.4 eV and the electron affinity $q\chi_s$ is 4.5 eV at 300K. Calculate the semiconductor work function $q\phi_s$. Also, draw the energy band diagrams (a) before and after contact formation at equilibrium (b) at a forward bias of 0.2 V and (c) reverse bias voltage of 3.2 V. Assume $n_i = 1.5\times10^{10}$ cm^{-3}. **[Ans: 4.642 eV]**

4. A metal-semiconductor junction is formed between an n-doped Si and aluminum. It is given that the Si has a doping concentration $N_d = 10^{17}$ cm^{-3} and a work function $q\phi_s$ = 4.191 eV, and aluminum has a work function $q\phi_m$ = 4.3 eV. Assume that kT = 0.026 eV, and Si has a bandgap of 1.1 eV and intrinsic concentration $n_i = 1.5\times10^{10}$ cm^{-3}. Deduce the electron affinity $q\chi_s$ of Si. Draw the energy band diagrams before and after the junction formation under equilibrium condition. Hence determine whether the junction formed is rectifying or ohmic. All the relevant energies must be clearly indicated in the band diagrams. **[Ans: 4.05 eV, Schottky contact]**

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TUTORIAL 11 Schottky Contacts and LED

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1. Consider a Schottky diode made on n-type Si ($N_d = 10^{16}$ cm^{-3}) with a barrier height of 0.67 eV. Given that the value of the Richardson's constant at 300 K is A* = 114 A/K^2-cm^2, deduce the reverse saturation current of the Schottky diode.

   [Ans: 66 μA/cm²]

   Now consider a p-n junction with the following parameters: $N_a = 10^{18}$ cm^{-3}, $N_d = 10^{16}$ cm^{-3}, $D_n = 25$ cm^2/s, $D_p = 10$ cm^2/s, $\tau_n = \tau_p = 0.1$ μs and $n_i = 1.5\times10^{10}$ cm^{-3}. Compute the reverse saturation current and compare it with that of the Schottky diode. Comment on the difference.

   [Ans: 36.7 pA/cm²]

2. A 300 μm thick single crystal Si wafer is subjected to incident light normal to the surface having power of 20 mW. You are given that the absorption coefficient is 5×10^4 cm^{-1} and the refractive index is 3.5 for Si at the frequency of the light.

   a) Determine the power absorbed within the first 0.2 μm, and the next 0.2 μm by the crystal. Comment on your results. **[Ans: 8.74 mW, 3.21 mW]**

   b) If the frequency of light is increased, would you expect an increase or a decrease in the amount of power absorbed? Account for your answer.

   c) Explain why it is unlikely that the energy absorbed in the Si wafer can be converted back into optical energy output through photon emission.

3. A GaAs n$^+$-p LED ($N_a = 5\times10^{16}$ cm^{-3}) is operated at a forward bias of 1 V. The electron diffusion coefficient and lifetime (in the p-region) are 30 cm^2/s and 10^{-8} s, respectively. The bandgap of GaAs is 1.43 eV, the intrinsic carrier concentration is 2×10^6 cm^{-3} and the diode area is 1 mm^2. Given that the radiative recombination efficiency is 0.5, calculate the photon flux (number of photons emitted per second from the LED surface) and the optical power generated by the LED.

   [Ans: 1.1×10¹⁵ /s, 0.25 mW]

4. Consider a LED with a flat emitting surface. Show that the fraction of radiation F transmitted from the LED to air as the useful output is given by the equation

$$\mathbf{F} = \frac{1}{4}\left(\frac{\mathbf{n}_2}{\mathbf{n}_1}\right)^2 \left[1 - \left(\frac{\mathbf{n}_1 - \mathbf{n}_2}{\mathbf{n}_1 + \mathbf{n}_2}\right)^2\right]$$

   where n_1 and n_2 are refractive indices of LED and air, respectively.

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TUTORIAL 12 Junction Photodetector

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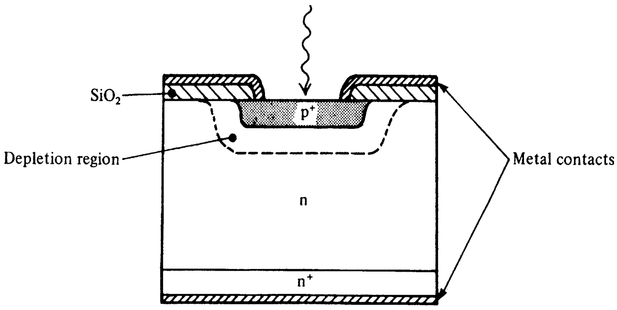
1. Consider the p^+-n silicon photodiode shown in the figure.



Given that the n layer is doped with $N_d = 5\times10^{21}\ m^{-3}$, and under a reverse bias voltage of 100 V, calculate x_n, the depletion width of the n region. Given that the p layer has a thickness of w_p, calculate the fraction of the light radiation at wavelength λ being absorbed in x_n. You are given that the refractive index (n) and the absorption coefficient (α) of Si at λ are 3.5 and $10^5\ m^{-1}$ respectively. Assume that $w_p << \alpha^{-1}$ and $\varepsilon_r = 11.8$ for Si. **[Ans: 5.1 μm, 0.276]**

If the fraction of light being absorbed in x_n is to be increased to 0.6, calculate the required reverse bias voltage. Comment and hence discuss why a p-i-n junction detector is desirable. **[Ans: 1589 V]**