NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2021-22
SEMESTER 2

EE2003 Semiconductor Fundamentals

TUTORIAL 6 Carrier Transport and Semiconductor in Non-Equilibrium

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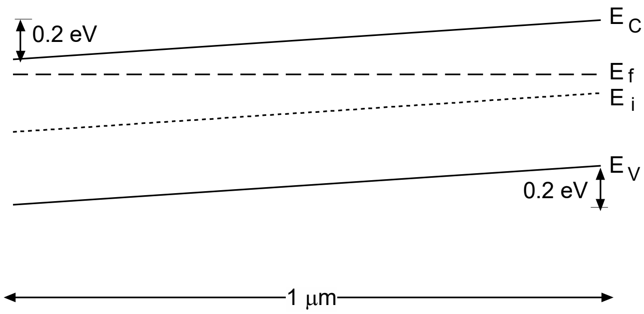
You may assume a temperature of 300 K for all your calculations unless stated otherwise.

1. The energy band diagram of a semiconductor is shown in the figure below.

   (i) What is the effective electric field for electrons?

   (ii) What is the direction of the electron diffusion current?

   (iii) What is the direction of the electron drift current?



2. A p-type silicon sample has an acceptor doping concentration of 1×10^{16} cm^{-3}. It is uniformly irradiated with light of an appropriate wavelength, resulting in the generation of electron-hole pairs (EHPs) at a rate of $G_L = 1\times10^{17}$ cm^{-3}s^{-1}. Assume the excess minority-carrier lifetime $\tau_n = 10$ μs.

   (a) Is the low-level injection condition valid? Justify your answer.
   (b) What is the maximum EHP generation rate that would ensure that the low-level injection condition remains valid?

[1×10^{12} cm^{-3}; 1×10^{20} cm^{-3} s^{-1}]

3. A silicon sample at 300 K is n-type with $N_d = 5\times10^{16}$ cm^{-3} and $N_a = 0$. The sample has a length of 0.1 cm and a cross-sectional area of 10^{-4} cm^2. A voltage of 5 V is applied between the ends of the sample. For $t < 0$, the sample is illuminated with light, producing an excess-carrier generation rate of 5×10^{21} cm^{-3}s^{-1} uniformly throughout the entire silicon. The minority carrier lifetime is 0.3 μs. At $t = 0$, the light is turned off. Derive the expression for the current in the sample as a function of time for $t \geq 0$. Assume $\mu_n = 1350$ cm^2/Vs, $\mu_p = 480$ cm^2/Vs and $n_i = 1.5\times10^{10}$/cm^3

[Ans: $54 + 2.2\exp(-t/\tau_{p0})$ mA]

4. Consider a semi-infinite p-type Si bar doped homogeneously to a value of 1.39×10^{16} cm^{-3}. The applied electric field is zero. A minority carrier concentration is electrically injected at one end of the sample (x = 0) such that the excess minority carrier concentration at x = 0 is 2.49×10^{13} cm^{-3}. The electron lifetime is 1×10^{-6} s. Assume that the sample temperature is 300 K and the electron mobility μ_n = 1450 $cm^2/V.s$

a. Write down the expression for the steady state excess electron concentration as function of x.

b. Calculate the electron diffusion current density at x = 0 and x = 10 µm.

[24.4 mA cm^{-2}; 20.7 mA cm^{-2}]

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TUTORIAL 7 PN Junction in Thermal Equilibrium

You may assume a temperature of $300\ \mathrm{K}$ for all your calculations unless stated otherwise. The following parameters apply to silicon (Si) at $300\ \mathrm{K}$:

Effective density of states in the conduction band, N_C	$2.80\times10^{19}\ \mathrm{cm}^{-3}$
Effective density of states in the valence band, N_V	$1.04\times10^{19}\ \mathrm{cm}^{-3}$
Intrinsic carrier concentration, n_i	$1.5\times10^{10}\ \mathrm{cm}^{-3}$
Band gap energy, E_g	1.12 eV
Relative permittivity, ε_r	11.8
Electron mobility, μ_n	1450 cm^2/V-s
Hole mobility, μ_p	450 cm^2/V-s

1. An abrupt Si *pn* junction is doped uniformly with $1\times10^{17}\ \mathrm{cm}^{-3}$ acceptor impurity on one side and $1\times10^{16}\ \mathrm{cm}^{-3}$ donor impurity on the other side.

   a. Determine the position of the Fermi level with respect to the valence band edge in the *p*-region and with respect to the conduction band edge in the n region.

   b. Draw the energy band diagram of the *pn* junction under thermal equilibrium and determine the contact or built-in potential V_{bi} from the diagram.

   c. Using the depletion approximation, calculate the following parameters of the pn junction under thermal equilibrium:

      i. Width of the space charge region x_{no} on the *n*-type side;
      ii. Width of the space charge region x_{po} on the *p*-type side;
      iii. Total width W_o of the space charge region;
      iv. Maximum electric field ξ_m in the space charge region.

      Comment on the values of x_{no}, x_{po} and W_o.

   d. Sketch the electric field distribution across the *pn* junction. With reference to the neutral *p*-region, determine the potential V at $x = 0$ (metallurgical junction) and compare it to the built-in potential determined in (b).

[0.120 eV; 0.206 eV; 0.794 V; 0.307 µm; 0.0307 µm; 0.338 µm; –4.70×10⁴ V/cm; 72.1 mV]

2. Show that the Fermi levels on the *n*-side and *p*-side of a *pn* junction at thermal equilibrium are constant with respect to distance throughout the junction (i.e. a single horizontal line on the energy band diagram).

   (Hint: Make use of the fact that the electron and hole current density across the junction are each equal to zero under thermal equilibrium and show $dE_F/dx = 0$*;* E_F *is the Fermi level.*

3. Consider a uniformly doped abrupt pn junction at 300 K. At thermal equilibrium, it is designed such that 10 % of the total depletion width region lies in the *p*-region. You are given that the built-in potential is 0.8 V. Determine the doping concentration N_a and N_d of the *p*- and *n*-region, respectively, and the total depletion width.

   [2.59×10^{16} cm^{-3}; 2.33×10^{17} cm^{-3}; 0.212 μm]

4. The magnitude of the peak electric field in a Si *p-n* junction is 20 kV/cm under thermal equilibrium conditions. If the built-in potential is 0.8 V, what is the donor doping if $N_a >> N_d$? Assume $\varepsilon_r = 11.8$, $\varepsilon_0 = 8.85\times10^{-14}$ F/cm, $q = 1.6\times10^{-19}$ C.

   [Ans: $N_d = 1.63\times10^{15}$cm^{-3}]

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TUTORIAL 8 PN Junction under an External Voltage Bias

You may assume a temperature of 300 K for all your calculations unless stated otherwise. The following parameters apply to silicon at 300 K :

Effective density of states in the conduction band, N_C	2.80×10^{19} cm^{-3}
Effective density of states in the valence band, N_V	1.04×10^{19} cm^{-3}
Intrinsic carrier concentration, n_i	1.5×10^{10} cm^{-3}
Band gap energy, E_g	1.12 eV
Relative permittivity, ε_r	11.8
Electron mobility, μ_n	1450 cm^2/V-s
Hole mobility, μ_p	450 cm^2/V-s

1. An abrupt Si *pn* junction is doped uniformly with 1×10^{16} cm^{-3} impurity on the *n*-side and 1×10^{17} cm^{-3}, impurity on the *p*-side. The cross-sectional area of the *pn* junction is 1×10^{-4} cm^2. Calculate the following parameters under (i) a forward bias of 0.65 V and (ii) a reverse of 2 V. Draw the energy band diagram under both biasing conditions, indicating clearly the extent of the band bending.

   a. Contact potential;
   b. The total depletion width;
   c. The depletion width in the *n*- and *p*-side;
   d. The space charge in each side of the depletion region;
   e. Peak electric field.

[0.104 V; 2.75 V; 0.122 μm; 0.628 μm; 0.111 μm; 0.011 μm; 1.76×10^{-12} C; -1.69×10^{4} V/cm; 0.571 μm; 0.057 μm; 9.12×10^{-12} C; -8.73×10^{4} V/cm]

2. A silicon *p-n* junction diode has the following parameters at 300 K, D_n = 25 cm^2/sec, D_p = 10 cm^2/sec, $\tau_n = \tau_p$ = 0.5 μs, ε_r = 11.7, $n_i = 1.5\times10^{10}$ /cm^3. Given that the electron diffusion current is 20 A/cm^2 and the hole diffusion current is 5 A/cm^2 at a forward bias of 0.65 V, determine the doping densities of the p and the n-regions of the diode.

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

3. Show that the ratio of the hole and electron currents injected across an ideal pn junction is given by

$$\frac{J_{\mathrm{p}}\left(x=x_{\mathrm{n}}\right)}{J_{\mathrm{n}}\left(x=-x_{\mathrm{p}}\right)}=\frac{L_{\mathrm{n}}\sigma_{\mathrm{p}}}{L_{\mathrm{p}}\sigma_{\mathrm{n}}}$$

where σ_{n} and σ_{p} are the conductivities of the *n*- and *p*-regions, respectively; You may assume the base lengths to be much longer than the respective minority carrier diffusion lengths.

Assuming L_{n} and L_{p} are comparable, what is the implication if the *p*-region is doped much more heavily than the *n*-region?

4 Consider two ideal *p-n* junction diodes A and B at 300 K with the same diode current of 15 mA. Calculate the forward bias voltages applied if the reverse saturation current I_{o} is (a) 5 μA for A and (b) 8 pA for B. If the diodes are made of two different semiconductor materials, which one would have smaller energy bandgap? Explain briefly.

[0.2 V, 0.53 V]

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EE2003 – Semiconductor Fundamentals

TUTORIAL 9 PN Junction Capacitances; Metal-Semiconductor Contacts

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You may assume a temperature of 300 K for all your calculations unless stated otherwise. The following parameters apply to silicon at 300 K :

Effective density of states in the conduction band, N_C	2.80×10^{19} cm^{-3}
Effective density of states in the valence band, N_V	1.04×10^{19} cm^{-3}
Intrinsic carrier concentration, n_i	1.5×10^{10} cm^{-3}
Band gap energy, E_g	1.12 eV
Relative permittivity, ε_r	11.8
Electron mobility, μ_n	1450 cm^2/V-s
Hole mobility, μ_p	450 cm^2/V-s

1. Room temperature (300 K) measurements on an abrupt Si p^+-n junction 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 the area of the junction is 2×10^{-3} cm^2, determine the built-in potential and the doping density of the n-side.

[0.83 V; 6.02×10^{15} cm^{-3}]

2. Consider an abrupt Si p^+n junction with $N_d = 1\times10^{16}$ cm^{-3}. The area of the junction is 1×10^{-4} cm^2. 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 under a forward bias of 0.65 V.

[2.47 nF]

3. An ideal Schottky contact is formed on n-type Si with a donor impurity concentration of 1×10^{17} cm^{-3}. The metal work function $q\phi_m$ is 4.9 eV and the electron affinity $q\chi_s$ of Si is 4.05 eV at 300 K. Calculate the Si work function $q\phi_s$. Draw the energy band diagrams before and after contact formation under (a) thermal equilibrium; (b) a forward bias of 0.4 V and (c) a reverse bias of 3.2 V. What is the significance of the Schottky barrier height?

[4.20 eV]

4. Consider a metal-semiconductor junction at room temperature. Assume that the work function of the metal Φ_M is equal to the electron affinity of the semiconductor χ plus $3kT$. Also, assume that the Fermi level in the semiconductor is located $3kT$ below the conduction band edge E_C . The bandgap of the semiconductor is 1 eV. Determine:

   a) Whether the semiconductor is intrinsic, n-type or p-type.
   b) The value of the built in voltage V_{bi}.
   c) Whether the metal-semiconductor forms a rectifying or ohmic contact. Justify your answer using a band diagram with proper labeling. **[n-type, V_{bi} = 0 V]**