SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING
LRESE - Laboratory of Renewable Energy Sciences and Engineering

Solar Energy Conversion Devices and Plants: Exercise 6

In this exercise, you will solve in a 1 dimension and at steady state the transport and conservation equations for electron and holes in a solar cell with a pn junction to determine the electric field, the photo-carrier density and the performance of the cell. This is an individual work that will be graded (average of 2 out of 3 computational exercises will be 22% of final mark). Submission deadline of code and short report is November 24, 2025, 14:15, by email to Prof. Haussener.

Solar cells: pn junction and performance

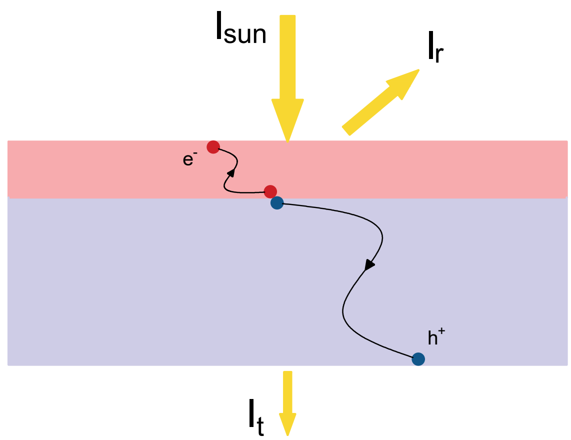

Figure 1: Scheme of the c-Si solar cell showing the input solar irradiation, and its reflected and transmitted portions.

Assumptions

a) Normal incident irradiation $I_{\text{sun}} = 1000\ \text{Wm}^{-2}$.

b) The total thickness of the solar cell is $W_\text{N} + W_\text{P} = 200\ \mu\text{m}$, the thickness of the n layer is $W_\text{N} = 300$ nm.

c) Both layers have a doping level concentration of 1e17 cm^{-3}.

d) The refractive index and extinction coefficients at a wavelength of 500 nm are $n = 4.293$ and $k = 0.045$.

e) Initial temperature of 300 K.

f) Constant electron and hole mobility of $\mu_\text{e} = 1360$ and $\mu_\text{h} = 450\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$.

g) Consider an electron and hole velocity recombination of $S_\mathrm{e} = 1\mathrm{e}4$ and $S_\mathrm{h} = 1\mathrm{e}3$ cms^{-1}.

h) The electron and hole life times are $\tau_\mathrm{e} = 2.9$ and $\tau_\mathrm{h} = 12.4$ μs, respectively.

Questions

a) Compute the built-in potential of the solar cell, V_bi.

b) Determine the depletion regions x_N and x_P at an external applied potential, $V_\mathrm{sc} = 0$.

c) Compute and plot the generation of photocarriers along the thickness of the solar cell, $G(x)$ (Use log scale for the abscissa).

d) Compute and plot the electron and hole concentration in the quasi-neutral regions by solving the transport and continuity equations (Use log scale for the abscissa and ordinate).

$$D_\mathrm{h}\frac{\mathrm{d}^2\Delta n_\mathrm{h}}{\mathrm{d}x^2} - \frac{\Delta n_\mathrm{h}}{\tau_\mathrm{h}} = -G(x)$$
$$D_\mathrm{e}\frac{\mathrm{d}^2\Delta n_\mathrm{e}}{\mathrm{d}x^2} - \frac{\Delta n_\mathrm{e}}{\tau_\mathrm{e}} = -G(x)$$

The boundary conditions for the quasi-neutral n region are the following:

$$\left.\frac{\mathrm{d}\Delta n_\mathrm{h}}{\mathrm{d}x}\right|_{x=0} = \frac{S_\mathrm{h}}{D_\mathrm{h}}\Delta n_\mathrm{h}(x=0)$$
$$n_\mathrm{h}\cdot n_\mathrm{e}\big|_{x=W_\mathrm{N}-x_\mathrm{N}} = n_\mathrm{i}^2\exp\left(\frac{qV_\mathrm{sc}}{kT}\right)$$

Similarly for the quasi-neutral p region:

$$n_\mathrm{h}\cdot n_\mathrm{e}\big|_{x=W_\mathrm{N}+x_\mathrm{P}} = n_\mathrm{i}^2\exp\left(\frac{qV_\mathrm{sc}}{kT}\right)$$
$$\left.\frac{\mathrm{d}\Delta n_\mathrm{e}}{\mathrm{d}x}\right|_{x=W_\mathrm{N}+W_\mathrm{P}} = -\frac{S_\mathrm{e}}{D_\mathrm{e}}\Delta n_\mathrm{e}(x=W_\mathrm{N}+W_\mathrm{P})$$

e) Compute and plot the total current density along the solar cell (Use log scale for the abscissa).

The total current density is the sum of the electron and hole current densities. However, we only have the current density of holes in the n-side, and the current density of electrons in the p-side, therefore it is not possible to sum them directly. However, it is possible to compute the hole current density in the p-side by neglecting the recombination term in the continuity equation when solving the depletion region.

$$J_{\mathrm{h,P}}|_{x=W_{\mathrm{N}}+x_{\mathrm{P}}} = J_{\mathrm{h,N}}|_{x=W_{\mathrm{N}}-x_{\mathrm{N}}} + q\int_{W_{\mathrm{N}}-x_{\mathrm{N}}}^{W_{\mathrm{N}}+x_{\mathrm{P}}} G(x)\mathrm{d}x$$
$$J_{\mathrm{tot}} = J_{\mathrm{h,P}}|_{x=W_{\mathrm{N}}+x_{\mathrm{P}}} + J_{\mathrm{e,P}}|_{x=W_{\mathrm{N}}+x_{\mathrm{P}}}$$

f) Compute and plot the electrostatic potential and electric field in the depletion region (Use log scale for the abscissa).

In this case the Poisson's equation has to be solved:

$$\boldsymbol{\nabla}^2\phi = \frac{q}{\epsilon}(n_0 - p_0 + N_{\mathrm{A}} - N_{\mathrm{D}})$$

with the following boundary conditions:

$$\phi|_{x=W_{\mathrm{N}}-x_{\mathrm{N}}} = V_{\mathrm{bi}} - V_{\mathrm{sc}}$$
$$\phi|_{x=W_{\mathrm{N}}+x_{\mathrm{P}}} = 0$$

where ϕ is the electrostatic potential and $E = -\frac{\mathrm{d}\phi}{\mathrm{d}x}$ is the electric field.

g) Compute and plot the I-V curve in the dark and when the cell is irradiated.

h) Compute the efficiency of the solar cell at 300 K and 400 K. Explain the differences.

Hints

Use the following expressions to compute the properties of c-Si:

$$\chi = 4.05 \text{ eV}$$
$$\epsilon = 11.7$$
$$Eg = 1.1695 - 4.73\text{e-4} \cdot T^2/(T + 636)$$
$$m_{\mathrm{e}}^* = [0.328 + 9\text{e-3} \cdot (T/300)] \cdot m_0$$
$$m_{\mathrm{h}}^* = [0.550 + 0.6 \cdot (T/300) - 0.1 \cdot (T/300)^2] \cdot m_0$$
$$\alpha = \frac{4\pi k}{\lambda}$$
$$\Delta n_{\mathrm{h}} = n_{\mathrm{h}} - p_0$$
$$\Delta n_{\mathrm{e}} = n_{\mathrm{e}} - n_0$$

where χ is the electron affinity, ϵ is the dielectric constant, m_0 is the free electron mass, n_h is the total concentration of holes, n_e is the total concentration of electrons, p_0 is the equilibrium concentration of holes, n_0 is the equilibrium concentration of electrons, and λ is the wavelength.