Solution Series 10

Exercise 1: Real solar cell

Consider a solar cell based on a simple p-n junction with the same emitter as described in Ex. 2 of Serie 6 and a p-doped base ($N_A = 10^{16}\,\mathrm{cm^{-3}}$) but this time with a finite thickness of $d = 180\,\mu\mathrm{m}$. The total thickness of the wafer is denoted by H. We assume that under AM1.5G illumination, the fill factor (FF) is 75 % and the short circuit current density (J_{sc}) is $44\,\mathrm{mA\,cm^{-2}}$. The purpose of this exercise is to get a feeling for the impact that the surface recombination velocities S_n and S_p, the lifetime τ and the saturation current density J_0 have on the cell efficiency.

a) Write down the V_{oc} as a function of J_0 with the help of the diode equation (one diode model) under illumination.

Solution:

Under illumination the diode equation for the one diode model is expressed by the following formula with the *thermal voltage* $V_T = kT/q$:

$$J(V) = J_0\left(\exp\left(\frac{V}{V_T}\right) - 1\right) - J_L \tag{1}$$

In open circuit condition the following holds:

$$J(V_{oc}) = 0 = J_0\left(\exp\left(\frac{V_{oc}}{V_T}\right) - 1\right) - J_L \tag{2}$$

$$\tag{3}$$

This leads to:

$$V_{oc} = V_T\left(\ln\left(\frac{J_L}{J_0} + 1\right)\right) \tag{4}$$

Usually $J_L/J_0 \gg 1$, and $J_L = J_{sc}$. Therefore you can eventually write:

$$V_{oc} = V_T\left(\ln\left(\frac{J_{sc}}{J_0}\right)\right) \tag{5}$$

b) Explain why J_{0E} increases with the doping (starting from approx. $10^{19}\,\mathrm{cm^{-3}}$) for a constant S_p using Fig. 1.

Solution:

At high doping levels, recombination is dominated by the Auger process. As has been shown in previous lectures, the Auger lifetime is $\propto N^{-2}$ at low injection and $\propto \Delta n^{-2}$ at high injection. So increasing the doping will lead to a reduction in lifetime and diffusion length which will eventually increase the saturation current.

c) Explain why $J_{0\mathrm{E}}$ increases strongly for S_p higher than $10^3\,\mathrm{cm\,s^{-1}}$, if the doping is decreased below 10^{19}.

Solution:

For low doping levels, typically below $10^{18}\,\mathrm{cm^{-3}}$, the diffusion length of holes is larger than the emitter thickness and the electrical field at the junction is reduced (going towards flat band conditions). This means that the holes are able to reach the interface at the front and if the latter is not well passivated the probability is high that they recombine there which will drastically increase $J_{0\mathrm{E}}$.

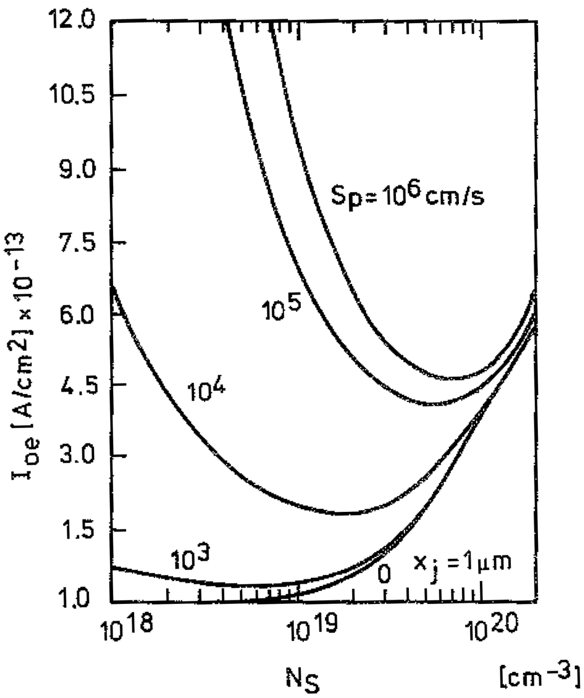

Figure 1: Saturation current of an emitter as a function of surface concentration, with S_p being parameter. Taken from *Crystalline silicon solar cells* by A. Goetzberger, J. Knobloch, and B. Voss.

Exercise 2: Geometry factor

The following exercise will treat the so-called geometry factor G_F which influences the base saturation current $J_{0\mathrm{B}}$ given by:

$$J_{0\mathrm{B}} = \frac{q \cdot n_i^2 \cdot D_n}{N_\mathrm{A} \cdot L_n} \cdot G_\mathrm{F} \tag{6}$$

G_F is determined by the two variables S_n/S_∞ and H/L_n, where S_∞ is the bulk recombination velocity defined as D_n/L_n. The relationship between those parameters is shown in Fig. 2.

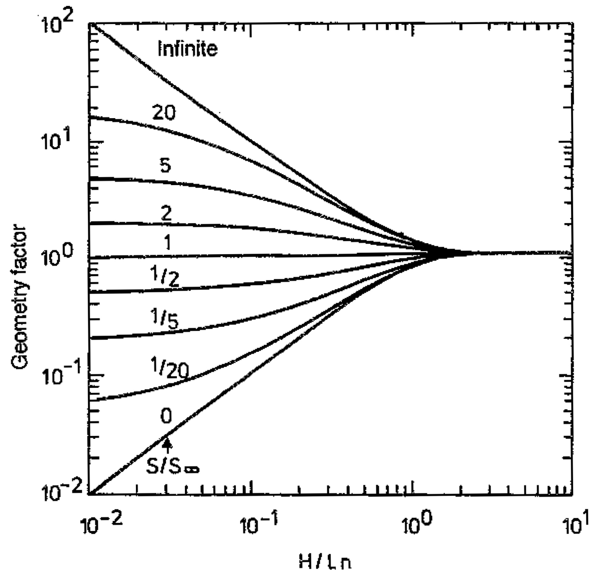

Figure 2: Geometry factor as function of the ratio base thickness H / diffusion length L_n. Taken from *Crystalline silicon solar cells* by A. Götzberger, J. Knoblauch, and B. Voss.

a) Explain Fig. 2 in your own words.

Solution:

The geometry factor as function of H/L_n can roughly be divided into two regions: $H/L_n > 1$ and $H/L_n < 1$. In case the diffusion length L_n is smaller than the base width H most of the carriers generated in the base won't reach the surface, this is especially true for an infinite base as treated in Ex. 2. If however, L_n is of the same order of magnitude as H and larger, the carriers will be able to reach the surface and recombine. In that case the surface passivation quality plays an important role for $J_{0\mathrm{B}}$. If the latter is good (bad), i.e. $S_n < S_\infty$ ($S_n > S_\infty$), $G_\mathrm{F} < 1$ ($G_\mathrm{F} > 1$) and $J_{0\mathrm{B}}$ will be reduced (increased).

The rest of this exercise is OPTIONAL but we recommend to you to at least have a look at the solutions posted on the Moodle.

b) Extract the value of the G_F for $\tau = 1\,\mathrm{ms}$ from the graph and three different values of surface recombination velocity $S_n = 10^1$, 10^3, 10^7 $\mathrm{cm\,s^{-1}}$. Use $H = 180\,\mathrm{\mu m}$ and $D_n = 28\,\mathrm{cm^2\,s^{-1}}$.

Solution:

Remember that $L_n = \sqrt{D_n \cdot \tau_n}$ and $S_\infty = \frac{D_n}{L_n}$

Table 1: Results for $\tau = 1\,\text{ms}$.

S_n [cm s^{-1}]	10^1	10^3	10^7
L_n [cm]	0.167	0.167	0.167
H/L_n	0.108	0.108	0.108
S_n/S_∞	5.98×10^{-2}	5.98	5.98×10^4
G_F	0.1	4	10

c) With the values obtained in part b) calculate the corresponding base saturation current values, the total saturation current density $J_0 = J_{0\text{E}} + J_{0\text{B}}$, the V_oc and eventually the efficiency η. Use the following values: $D_n = 28\,\text{cm}^2\,\text{s}^{-1}$, $n_i^2 = 10^{20}\,\text{cm}^{-6}$, $J_{0\text{E}} = 2 \times 10^{-13}\,\text{A}\,\text{cm}^{-2}$, $J_\text{sc} = 44\,\text{mA}\,\text{cm}^{-2}$ and $FF = 75\,\%$.

Solution:

Reminder from ex.1: $N_A = 10^{16}\,\text{cm}^{-3}$

The V_oc is derived in the exercise 1: $V_{oc} = \frac{kT}{q} \ln\left(\frac{J_{sc}}{J_0}\right)$

With the thermal velocity at 300 K: $V_T = \frac{kT}{q} = \frac{8.617 \cdot 10^{-5} \cdot 300}{1} = 2.59 \cdot 10^{-2}$ [eV]

Table 2: Results for $\tau = 1\,\text{ms}$.

S_n[cm s^{-1}]	10^1	10^3	10^7
G_F	0.1	4	10
$J_{0\text{B}}$ [A cm^{-2}]	2.68×10^{-14}	1.07×10^{-12}	2.68×10^{-12}
J_0 [A cm^{-2}]	2.27×10^{-13}	1.27×10^{-12}	2.88×10^{-12}
V_oc [mV]	672	627	606
η [%]	22.2	20.7	20.0

d) Change the lifetime to $\tau_n = 1\,\mu\text{s}$ and calculate again.

Solution:

The results are given in table 3. Note that the diffusion length of the electrons is so much smaller compared to the base width. Therefore they can not reach the rear surface and as a result the geometry factor and the base saturation current at the rear surface does not depend on the surface recombination velocity S_n.

Because of their very short lifetime, the electrons recombine before reaching the rear surface. Thus $J_{0\text{B}}$ is constant even if the surface recombination velocity is reduced. The efficiency is no longer limited by the passivation but by the base lifetime.

e) Is the efficiency realistic?

Solution:

No. Indeed, the lifetime of electrons in the Base is so small that the photo-generated electrons can not be collected. Consequently the obtained current J_sc is smaller than $44\,\text{mA}\,\text{cm}^{-2}$ and the resulting efficiency is lower.

Table 3: Results for a lifetime $\tau = 1\,\mu s$.

S_n [$\mathrm{cm\,s^{-1}}$]	10^1	10^3	e7
G_F	1	1	1
J_{0B} [$\mathrm{A\,cm^{-2}}$]	8.47×10^{-12}	8.47×10^{-12}	8.47×10^{-12}
J_0 [$\mathrm{A\,cm^{-2}}$]	8.67×10^{-12}	8.67×10^{-12}	8.67×10^{-12}
V_{oc} [mV]	578	578	578
$\eta(\%)$	19.1	19.1	19.1

f) Imagine $S_n \to 0$ and $\tau_n \to \infty$. Calculate J_{0B}. Which part of the saturation current dominates and limits the efficiency? What is the maximum achievable efficiency?

Solution:

If $S_n \to 0$ and $\tau_n \to \infty$, J_{0B} is close to $10^{-15}\,\mathrm{A\,cm^{-2}}$ because of $G_F = 10^{-2}$. Thus J_{0B} is negligible compared to $J_{0E} = 2\times10^{-13}\,\mathrm{A\,cm^{-2}}$ which will limit both the V_{oc} and the efficiency. The value that can be reached is around 22.3%.