Solution to Exercise 8.1-3

Characteristics of Real Solar Cells

Illustration

This is the starting point for doing the exercise:

$$I = I_1 \cdot \left(\exp \frac{e U_{eff}}{kT} - 1 \right) + I_2 \cdot \left(\exp \frac{e U_{eff}}{nkT} - 1 \right) + \frac{U_{eff}}{R_{SH}} - I_{Ph}$$

$$U_{eff} = U - I \cdot R_{SE}$$
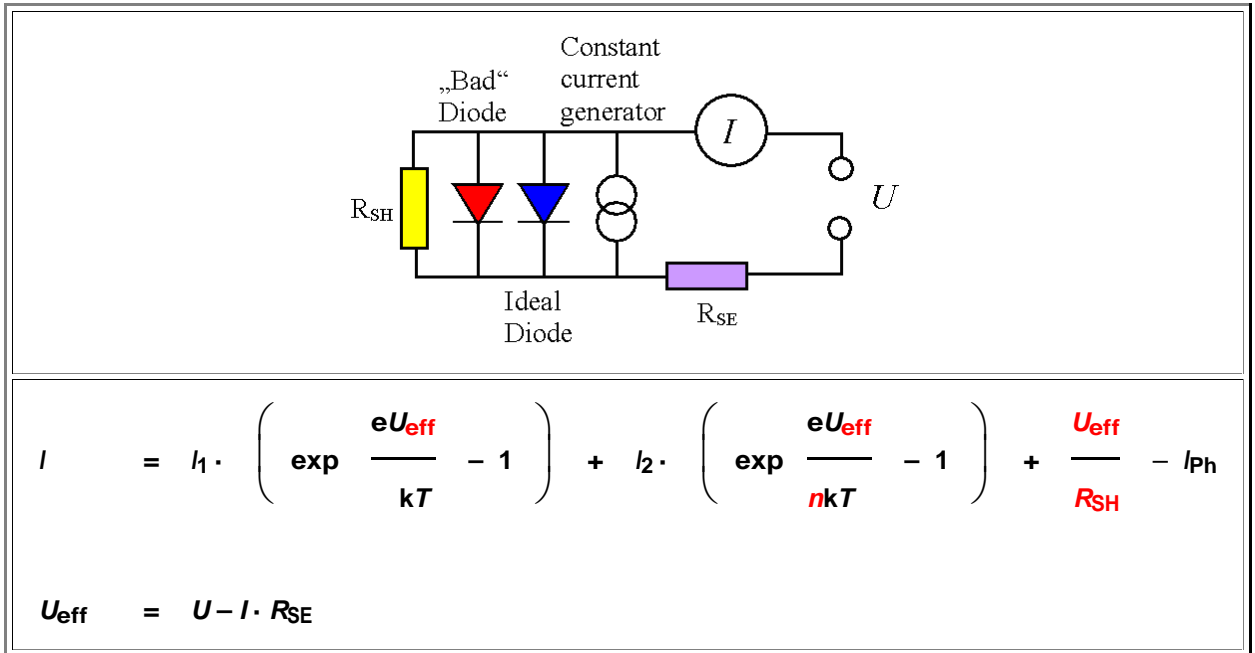
Discuss *qualitatively* the influence of the *two resistors* (and, as a more minor point, the *idealiy factor n*) on the **IV** characteristics.

We will get to this, but here we will actully discuss the questions first *quantitatively*. As input parameters we need j_1, j_2 and the ideality factor **n**, which we take as (see also exercise 8.1-5)

- $j_1 = 10^{-9}$ **A/cm^2**.
- $j_2 = 10^{-7}$ **A/cm^2**.
- **n = 2**.

All we have to do is to solve the the equation from above numerically for various values of the parameters:

- Series resistance R_{SE}.
- Shunt resistance R_{SH}.
- Diode ideality factor **n**.
- Pre-exponential factors I_1 and I_2.
- And possibly the whole thing as a function of temperature **T**.

This is a big program, but it is not too difficult to see some major points.

Series resistance R_{SE}

Here is a plot of the **IV** characteristics of a *typical* solar cell with **5** different series resistances R_{SE}.
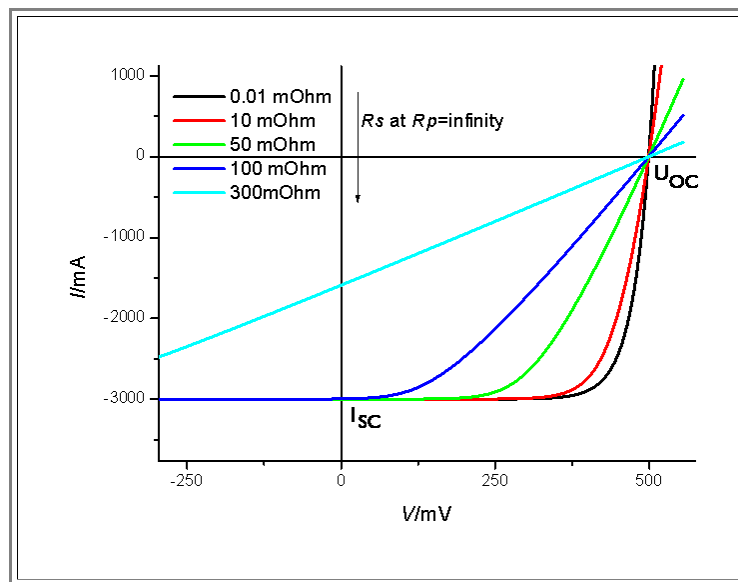
- Everything else has been kept "ideal". This means that the shunt resistance R_{SH} is very large ("infinity"), the ideality factor of the second diode is $n = 2$, and the two pre-exponential factors are $I_1 = 0,1$ µA and $I_2 = 10$ µA. The photo current is **3 A**.

Even without looking a the (numerically) calculated figure, we can deduce *qualitatively* a few facts from our basic equation above, aw asked in the exercise.

- For $I = 0$ A, we have $U_{eff} = U$. That means that *all* *IU*-characteristics *must* run through U_{OC}, no matter what kind of serial resistance we might have.

- For large negative U (*reverse direction*) , the current I is simply constant. We loose a part of the applied voltage in the serial resistance, but that does not effect the current. The characteristics in the **3rd** quadrant thus does not depend on R_{SE} if $|U|$ is large enough.

- For large positive U (*forward direction*), the diode by itself will admit large currents for voltages above about **0.5 V**, i.e. the *diode resistance* becomes very low. The *IU*-characteristics then *must* be dominated by R_{SE}; it will simply turn into an ohmic *straight line* with a slope given by $1/R_{SE}$

- In the fourth quadrant for voltages below U_{OC} some of the voltage drops a the series resistor. The magnitude of the current thus can only be lower than in the case without a series resistor.

All of this is exactly what the calculated figure shows- taking into account the "Ohmic" straight line we could have derived most of the graph above without any quantitative calculations

We now can draw several conclusions:

- **1.** The efficiency η is proportional to the product of $I_{Sc} \cdot U_{OC} \cdot FF$. As long as R_{SE} is not too large (e.g. $R_{SE} < 100$ mΩ for the example given), series resistances primarily decrease the fill factor FF and thus reduce the efficiency η.

- **2.** While in normal "electrical" life, "*milliohms*" hardly count, a few mΩ serial resistance are enough to make your solar cell measurable worse.

- **3.** Given the specific resistivity of good metals of $\rho \approx 2$ **µΩcm**, a **Cu** wire of **1 cm** length and **1 mm^2** cross section has a resistance of $R = 2$ mΩ. The cross sectional area of the grid metallization on a solar cell is **< 1 mm^2**, which means *we have a real and unavoidable problem* with series resistances of real solar cells!

Shunt resistance R_{SH}

Here is a plot of the *IV* characteristics of a *typical* solar cell with **4** different shunt resistances R_{SH}.
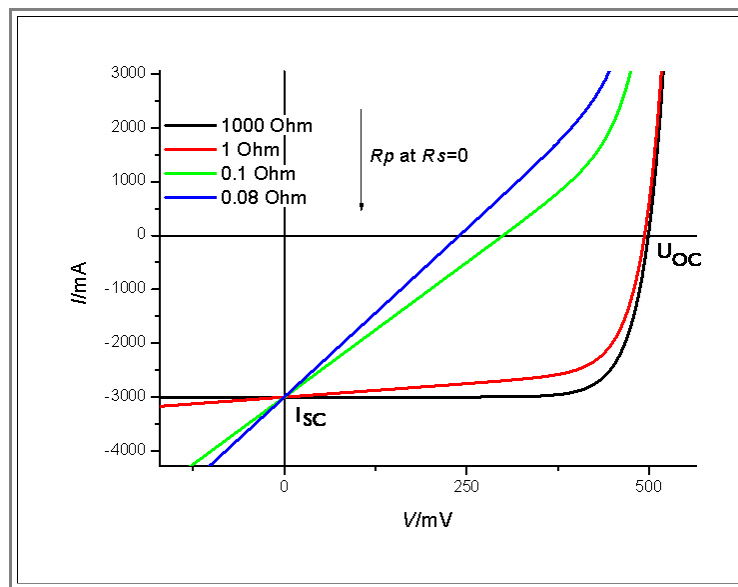
- Everything else has been kept "ideal". This means that the series resistance R_{SE} is now close to zero.

- Again, without looking a the (numerically) calculated figure, we can easily deduce *qualitatively* what is going to happen.

  - $U_{eff} = U$ is always true. For $U_{eff} = U = 0\ V$ *all* characteristics must run through I_{SC} since the term U_{eff}/R_{SH} is zero.

  - Otherwise, for any voltage U in *reverse* and *forward* direction we have a current $I_{SH} = U_{eff}/R_{SH}$ that must be added to the diode current and thus shifts the total current *upwards* (towards *larger* values (**-1** is larger than **-2**!) and thus decreases its *magnitude* in the fourth quadrant by just U_{eff}/R_{SH}. The flat part of the ideal characteristic thus turns into a straight line with slope $1/R_{SH}$

  - In the fourth quadrant, where it counts, we will loose voltage *and* fill factor and thus severely reduce the efficiency η.

  - We also have a reverse current increasing linearly with the reverse voltage - very bad in a module!

- All of this is exactly what the calculated figure shows- taking into account the "Ohmic" straight line centered at I_{SC} we could have derived most of the graph above without any quantitative calculations

- We now can draw several conclusions:

  - **1.** The efficiency η is proportional to the product of $I_{Sc} \cdot U_{OC} \cdot FF$. As long as R_{SH} is not too small ($> \approx 1\Omega$) for the example given, shunts are not too bad. Real short circuits $< \approx 1\Omega$, however, are disastrous for the efficiency.

  - **2.** Since the **pn**-junction is very large and extends all the way out to the *edge* of the solar cell, we must expect that local short circuits happen. The rather difficult question coming up now is how a few *local* short circuits affect the *global* solar cell.

- We have now answered the exercise questions.

  - However, we will go on and discuss a few more points.

Ideality factor *n*

- Here is a plot of the *IU* characteristics of a *typical* solar cell with deviations from ideality expressed in the ideality factor *n* and the pre-exponential factors I_1 and I_2
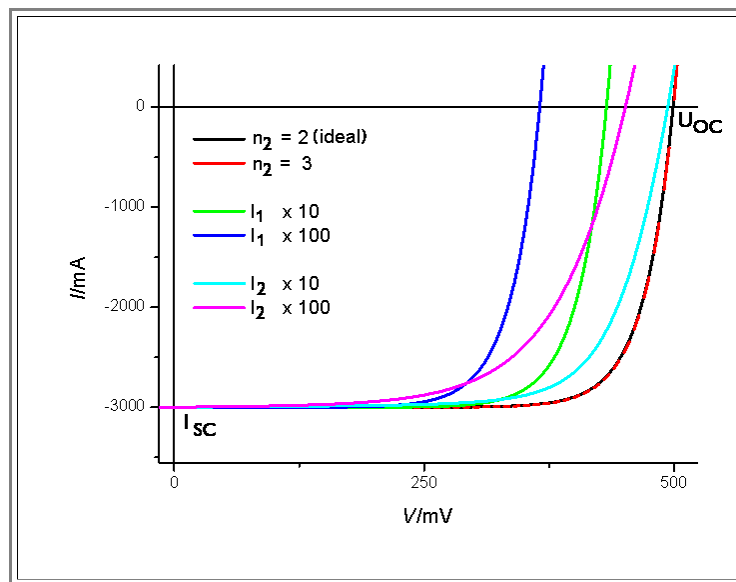
● Everything else has been kept simple - no shunt or series resistors. This means that the shunt resistance R_{SH} is very large ("infinity"), R_{SE} is zero. The ideality factor of the second diode is $n_2 = 2$ or $n = 3$ (the ideality factor of the first diode is always $n_1 = 1$ by definition), and the two pre-exponential factors are $I_1 = 0,1$ µA and $I_2 = 10$ µA as starting values once more, but also **10** times and **100** times that number. The photo current is **3 A**.

Without looking a the (numerically) calculated figure, we *cannot* easily deduce what is going to happen.

● Well, looking a the figure, we see that changing the ideality factor of the second diode from **n = 2** to **n = 3** does not produce a noticeable change in the characteristics. The simple reason for this is that in reverse direction the exponentials in the *I(U)* equation don't matter, and that in the forward characteristics the ideal diode always "wins" except for small positive voltages.

● However, the relation between the two diodes is also influenced by the pre-exponential factors. Divided by the cell area, they were abbreviations for the following current densities:

$$ j_1 = \left(\frac{e \cdot L \cdot n_i^2}{\tau \cdot N_A} + \frac{e \cdot L \cdot n_i^2}{\tau \cdot N_D} \right) $$

$$ j_2 = \left(\frac{e \cdot n_i \cdot d(U)}{\tau} \right) $$

● Why did we pick *j₂* so much larger than *j₁*? We have, in fact, already discussed the relation *j₂ / j₁* for **pn**-junctions, even so you probably forgot it all, and found that *j₂ >> j₁* is unavoidable for **Si** and other semiconductors with bandgaps **<≈ 1 eV**. This is why the values chosen for the pre-exponential factors and given above have the relation they have.

● On the other hand, both factors are functions of variables like the diffusion length *L* or the recombination time τ, i.e. of crystal perfection; of the doping N_{Dop}; and of the temperature *T* (via the intrinsic carrier concentration n_i).

● *I₁* and *I₂* are thus variables up to a point, and we want them as small as possible because the currents they cause diminish the photo current and the open circuit voltage. The figure shows that clearly. Increasing *I₁* or *I₂* substantially, decreases U_{OC} and, for the case of *I₂*, also the fill factor **FF**.

● However, they should not be too small, either. If they would be zero, we would just have a constant photo current and no voltage ever builds up. The values chosen are rather optimal, that's why we called them "ideal".

Temperature *T*

Our basic equation on top contains the temperature explicitly in the two exponentials and implicitly in the two pre-exponential factors j_1 and j_2.

- The two equations right above for these two factors contain $n_i(T)$, the intrinsic carrier density, which grows exponentially with increasing temperature.
- On top of that, the lifetime τ might be temperature dependent as well as the series and parallel resistors, but we will neglect that here.

So what it the total effect of temperature? This is shown below for negligible resistances and an ideality factor $n = 2$.
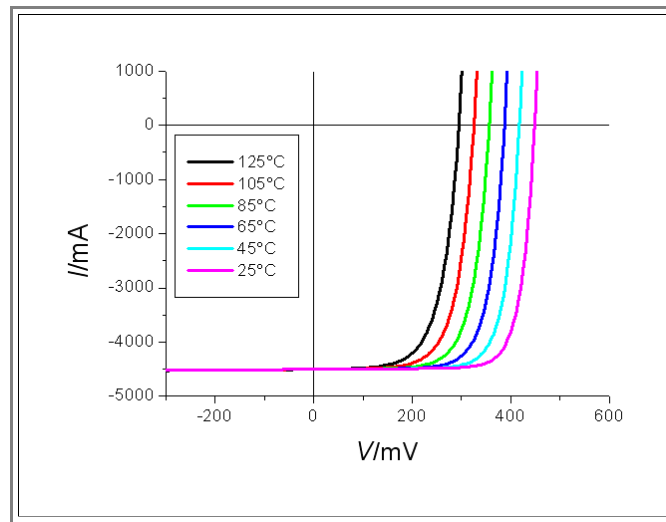
What we have is quite clear: As long as I_{Ph} does not depend on temperature (e.g. because we have a very good solar cell where all photo generated carriers are turned into photo current), the influence of the temperature comes from the exponents of our basic equation and from the (exponentially; via n_i)) temperature dependent j_1 and j_2

- The major effect is that the open circuit voltage decreases a lot (which is bad).

- Taking into account that I_{Ph} might be somewhat temperature dependent too (via the temperature dependence of the diffusion length, for example), that the series and shunt resistors most likely will be temperature dependent like most everything else, the situation can become quite complicated.

- However, the total effect is practically always that the efficiency comes down quite a bit with increasing temperature - high temperatures are bad for solar cells!

- This gives at least some comfort to cold and sun-deprived areas like Schleswig-Holstein. We may not have as much sun as the people in Spain or Sicily, but we don't have to worry as much about keeping our solar cells cool!

Final Conclusion

We now can draw some conclusions:

If you want to understand solar cells at the most fundamental non-trivial (= University) level, you better make damn sure that you understand the basic equation above and *all* its connotations by heart!

- That's not as difficult as it may appear! It's all in "Introduction to Materials Science II" - see chapter 6! That's why *we* spend so much time on the **pn**-junction *and* its finer details, which are not usually covered in standard undergraduate text books.