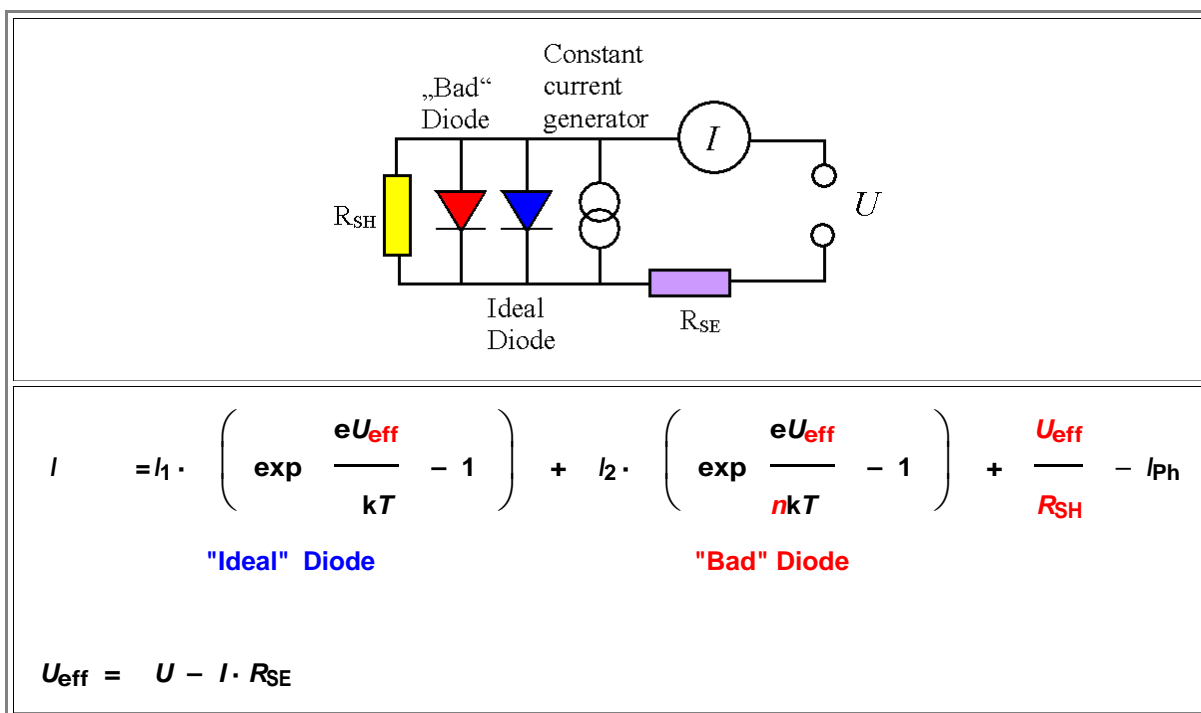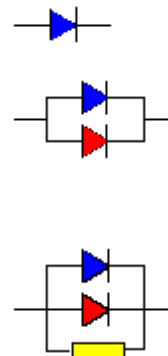## 8.1.2 Solar Cell Current-Voltage Characteristics and Equivalent Circuit Diagram

Basic Si Solar Cell

It is important to look a bit more closely at the *IV*-characteristics of a silicon **pn**-junction solar cell. The proper equation for that was already introduced before

- In a kind of short-hand notation, and because it is what electrical engineers always do, we could symbolize that with the normal diode symbol:

- However, it is customary to use a **"two diode" model**, where the first diode describes just the simple **pn**-junction behavior without carrirer generation and recombination in the space charge region (**SCR**), and the second diode, which then must be switched in parallel, describes the "non-ideality" of the real **pn**-junction. The equivalent circuit diagram then would consist of two diodes in parallel:

- Since our junctions area is **> 100 cm^2**, there might be regions where we have a *local* "**shunt**" in the junction. In the worst case this is a *local* short-circuit, caused for example because a metal particle was embedded in the junction (we obviously need to be clean if we make those junctions). The best we can do to model *globally* the many possibilties for shunts is to add a **shunt resistor R_{Sh}** in parallel to our diodes. "**Global**" in contrast to "**local**" means that we only care for whatever we can measure for the total solar cell, i.e. whatever we can get using only the two wires attached to it.

- If we now add the internal **series resistance** that is always there *in series* to what we already have, and consider that the photocurrent flowing across the junctions(s) is simply a **constant current generator** in electrical engineering terms, we obtain the final (and most simple) **equivalent cuircuit diagram** of a solar cell and a somewhat modified master equation for the *equivalent circuit diagram*:

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

"Ideal" Diode   "Bad" Diode

$$U_{eff} = U - I \cdot R_{SE}$$

It is easy to see how the master equation was changed.

- First we switched from current densities *j* to currents *I* and simply used the terms I_1 and I_2 as abbreviations for the pre-exponential factors. I_1 and I_2 belong to the first (=ideal) and second (non-ideal) diode in the equivalent circuit diagram.

- Next, we considered that the junction voltage U_{eff} is not identical to the externally measured voltage *U* but smaller by the voltage drop in the series resistor R_{SE}; i.e. $U_{eff} = U - I \cdot R_{SE}$.

- Then we generalized the non-ideal diode a bit by not just having a factor of two in the denominator of the exponent, but an ideality factor *n*. For *n=2* we would have the old equation, but since we arrived at that part by rather hand-waving approximations, real (non-ideal) diodes may be better described by some number other than **2**. Our ideal diode has *n=1*.

- Finally we add the current lost in the shunt resistor, which is given by U_{eff} / R_{SH}. We have a positive sign because this current must be opposed to the photo current, which has a negative sign in the conventions chosen.

Everything is quite clear - except that we can not solve this equation anymore analytically and plot **U(I)** curves with R_{SH}, R_{SE}, and *n* as parameters.

● We have reached a point where we need to do some exercise:

> ## Exercise 8_1_3
> *IV* characteristics of real solar cells

▶ It is absolutely essential that you do this exercise - at least ponder the question and look carefully at the solutions provided.

   ● You will learn that the series and shunt resistance does not only matter very much but that we need to have extremely low values for the series resistance in the order of at most a few **mΩ** per **(10 × 10) cm^2** solar cell.

   ● **Class Exercise:** *Cu has a specific resistivity of about* **2µΩcm**. *Given a solid Cu wire with* **1 mm^2** *cross section, what length will give you already* **10 mΩ**?

▶ OK - coming back from the exercise (or just the solution) you learned that:

   ● The **series resistance** really matters for high efficiency cells; i.e. for all solar cells with let's say η **> 10 %**. In fact, optimizing the series resistance of a standard commercial solar cells (now, in **2007**, with $\eta \approx$ **15 %**) is one of the major tasks in solar cell **R&D**. We will look at some number in another exercise coming up in the next module.

   ● The **shunt resistance**, if not extremely small, is less *obnoxious* for the efficieny η, but generates high leakage currents in reverse direction, increasing with the voltage. This is deadly in modules and thus cannot be tolerated either.

   ● As far as the ideality factor is concerned, we do not notice major problems. Here you have to look at details to see that the impact of the second diode is ther and detrimental.

▶ The way to lump everything together *globally* is to describe the global *IV*-characteristics with **3** numbers:

   ● **1.** The **fill factor** *FF*, defined as the relation between the area of the large yellow rectangle to the more orange area that is centered at the **optimal working point.**. That implies that the inner rectangle has the largest area of any rectangle (Area **=U · I=** power delivered by the solar cell). The fill factor measures the degree of "rectangularity" of the characteristics.

   ● **2.** The **open-circuit voltage** U_{OC}, i.e. the maximum voltage the solar cell will produce for the load resistor

   ● **3.** The **short-circuit current** I_{SC}.

   ● The **efficiency** η then is directly proportional to U_{OC}, I_{SC}, and *FF*, i.e.
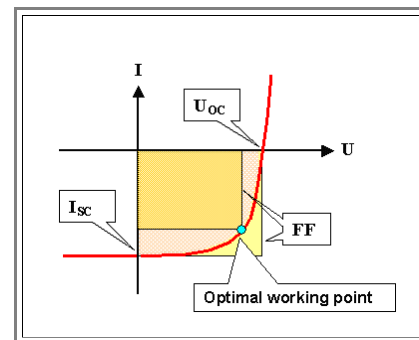
> $$\eta \ = \ \text{const} \cdot U_{OC} \cdot I_{SC} \cdot FF$$

▶ How do we **measure** the *IV*-characteristics of a real solar cell coming out of a production line?

   ● Easy, you might think: Apply a voltage, measure the current, change the voltage, measure the current again... Do it automatically by using a voltage ramp and keeping track of the current. Yes - that would be perfectly OK except that solar cells from a real production come off the line at the rate of about *1 solar cell per second*! Your measurement scheme is too slow for this because whenever the current changes the capacity of the **SCR** must be recharged and this takes some time.

   ● The way it is done is simple but powerful: You impress a constant current on your solar cell by some external power source. At a given illumination intensity this takes a certain voltage as determined by the *IV*-characteristics. If you change the illumination intensity, the voltage needed to drive the constant current changes, too. If you change your illumination intensity very quickly be just using a flash light, your voltage can follow just as quickly because you do not change the charge in the **SCR** capacitor.

   ● The *U(t)* curve for a fixed current contains all the information you want - but now you can get it with flashing speed!

▶ You will actually do this in a Lab course; the link provides the details.

Making Things Really Complicated

We are not yet done. Even if you have understood and committed to memory everything pointed out above with all its implications, at least two topics must be still be addressed:

1. How about other types of solar cells?
2. Connection between *local* and *global* parameters.

The *first* question can be dealt with rather easily - in principle:

- Whatever type of solar cell you have - **Si** bulk, **µ**-crystalline **Si** thin film type, amorphous **Si**, *CIGS* or **CdTe** thin films, *dye*-based **TiO$_2$** electrolytic cells - to name just a few, they must have some characteristics similar to a diode, and you can always find a suitable equivalent circuit diagram for modelling its behaviour.
- This equivalent circuit diagram might be somewhat different from the one given above, but you always have the problems associated with series and shunt resitances after you solved the basic junction problems.
- Quite often your choices for contacts are severely restricted and your series resistances get so large that you only can get decent efficiencies by switching them in series in relatively small units. More to that will be found in the link.

The second point is the difficult one. What he have discussed so far is the global behaviour of a solar cell - what you measure for the whole "global" **100 mm x 100 mm** cell, being uniformly illuminated.

- Now take your virtual knife and cut your solar cell into **10 000 (1 x 1) mm^2** cells (without any damage and so on), an measure the *IV*-characteristics of those **10 000** local solar cells. We assume that you know how to do this - it is possible *albeit* not easy.
- If your global solar cell was not very uniform (rather likely for many solar cell types), your local solar cells may show wildly different behaviour. The *IV* characteristics of the, let's say, **8** local cells that contain serious shunts (=short circuits) will be far more affected by this than your global cell (where you have another **9 992** shunt-free cells switched in parallel).
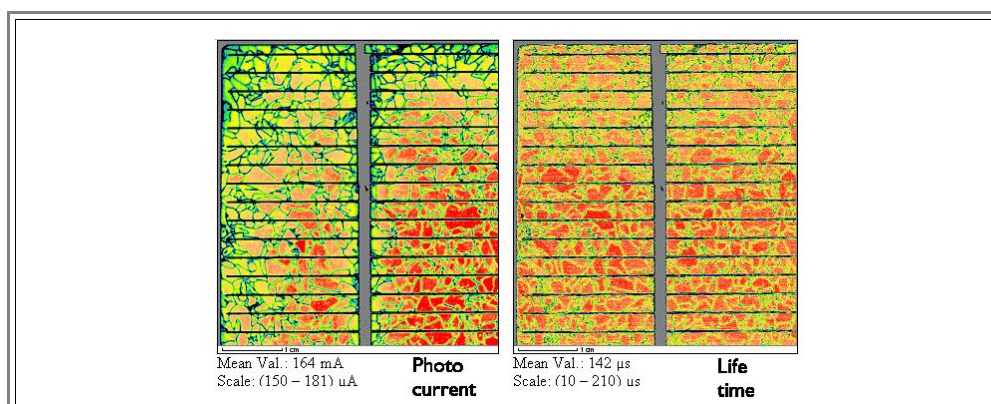
You get the point: Your major *global* parameters like short circuit current *I$_{SC}$*, open circuit voltage *U$_{OC}$*, fill factor **FF**, series and shunt resistances *R$_{SE}$* and *R$_{SH}$*, diode ideality factor *n*, are *somehow* determined by the local values, but it is not immediately obvious how.
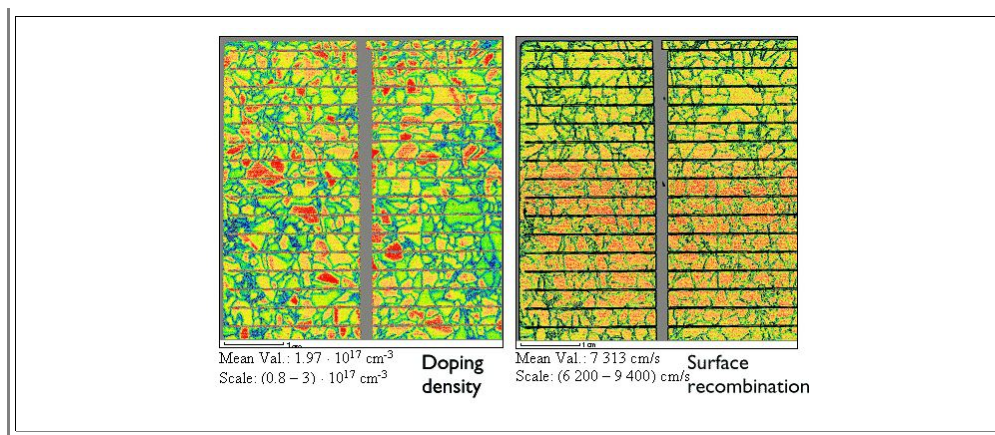
- Besides the *global* short circuit current *I$_{SC}$*, which obviously is just the sum of the *local* short circuit currents, for all other parameters the relationship between local and global parameters is non-trivial or very complex. In the case of the *global* ideality factor *n*, the number you extract from your global *IV* curves may not even have much to do with the junction properties.

Do we need to know the local parameters? After all, what counts is the real=global solar cell. If it is as good as it should be, the local parameters might be of no interest.

- Well - yes and no. Even if everything is OK globally, some small local defects may limit the life time of the solar cell, i.e. be a risk to its expected **20+** years of harvesting energy.
- More important, if you don't know your local parameters, you have very little guidance in making your solar cell better. If, for example, the *global* short circuit current is too low, that may indicate that it is just too low everywhere or that it might be allright on most parts of the cell but really lousy in some small areas. If you don't know what is the reason, you can't fix the problem.

To give an idea what we are talking about, look at the pictures of the "multi-crystalline" solar cell below:

Mean Val.: 164 mA
Scale: (150 – 181) uA
Photo current

Mean Val.: 142 µs
Scale: (10 – 210) us
Life time

Mean Val.: $1.97 \cdot 10^{17}$ cm^{-3} — Doping density
Scale: $(0.8 - 3) \cdot 10^{17}$ cm^{-3}

Mean Val.: 7 313 cm/s — Surface recombination
Scale: (6 200 – 9 400) cm/s

A perfect solar cell would show only one color - the optimal value. The colorful pictures thus demonstrate that there is room for improvement and that you have to have the information contained in the pictures to be able to make progress

How are maps like these obtained? With the so-called CELLO-Plus technique, developed in Kiel. This is a rather sophisticated characterization technique that is described in some more detail in the link.