INSTITUT FÜR ANGEWANDTE PHYSIK
Physikalisches Praktikum für Studierende der Ingenieurswissenschaften
Universität Hamburg, Jungiusstraße 11

Solar cells

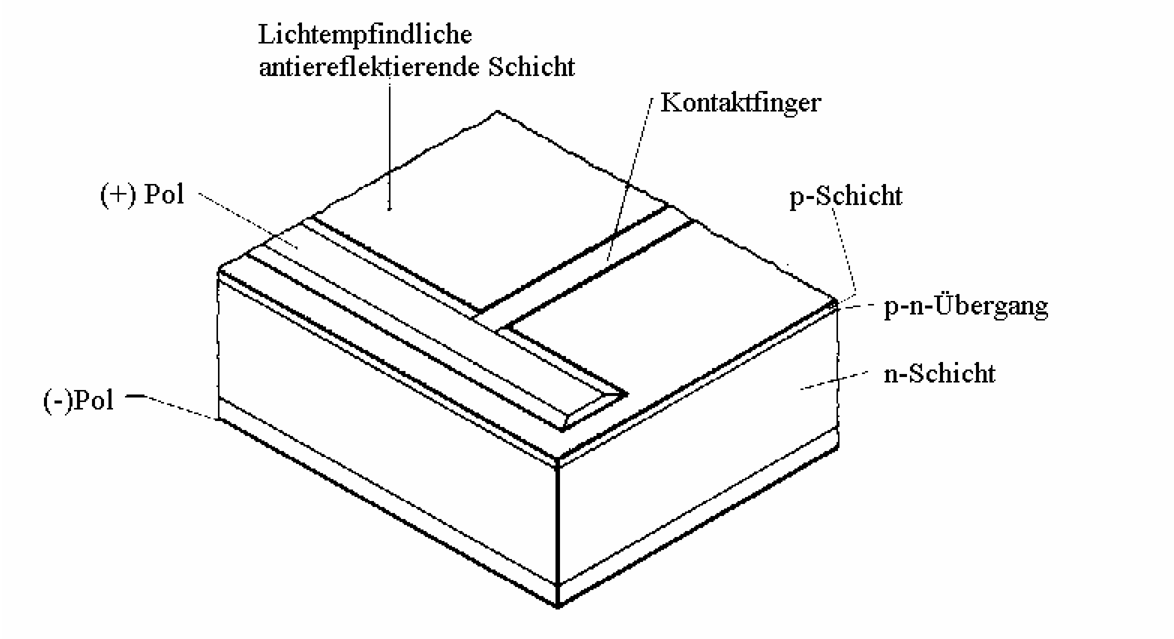


Fig. 1: Setup of a silicon solar cell.

1 How do solar cells produce electricity?

Nowadays most solar cell are made of silicon, a semiconductor. Semiconductors are materials that would be isolators at zero temperature which do not conduct electricity very well. However they have a small band gap of ~1 eV, which is much smaller than in isolators. Consequently even at room temperature the conduction band is populated with a few electrons, allowing for some conduction capability[1].

Not only the electrons in the conduction band but also the holes in the valence band contribute to conduction. A hole is a mobile vacancy that is left when an electron leaves the valence band to occupy the conduction band and thus is attributed a positive unit charge.

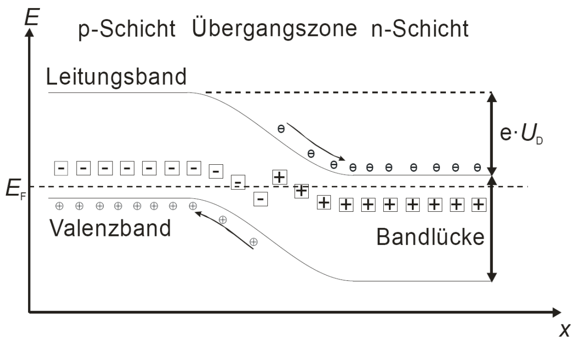
Doping of the tetravalent silicon with pentavalent (trivalent) atoms increases the electron (hole) conductivity. Silicon doped with pentavalent impurities is called n-silicon. The additional electron at the impurity does not take part in a bond to the neighboring silicon atoms, is therefore very mobile and can easily be transferred to the conduction band.

In n-type silicon the additional valence electrons thus increase conductivity. In an energy-band model these electronic states are depicted closely below the edge of the conduction band (Fig. 2).

In p-silicon, silicon doped with trivalent impurities, the new electronic states are closely above the valence band edge. At a cost of only ~1 meV a forth electron can participate in the bonds of such a trivalent atom to its neighboring silicon atoms and therefore leave a mobile hole in the valence band while completing the four bonds of the trivalent impurity to its neighbors.

The principle of a solar cell relies not so much on the improved conduction in doped semiconductors but on the effects taking place at a bridge from a p-type to an n-type semiconductor.

[1] Electrical conductivity requires partially occupied bands. This is the case in metals, their conduction band is partially filled. In Isolators however the conduction band is empty and the valence band is completely filled.



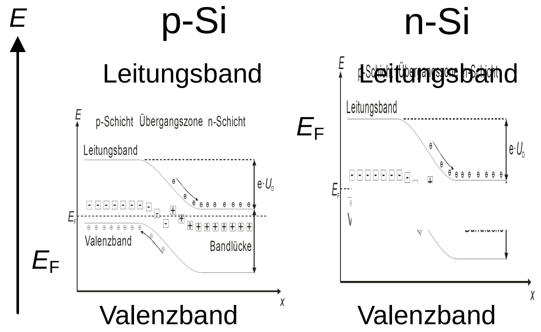


Fig. 2: Energy levels of the impurities (squares) and fermi energy E_F in the band gap of p- and n-doped silicon.

Fig. 4: p-n-junction after equilibration of the fermi levels.
U_D: *diffusion potential*
e: elementary charge

In the transition zone electrons diffuse from the n-type to the p-type semiconductor and holes do so vice versa. An interfacial zone emerges in which there are practically no mobile charge carriers left because electrons (holes) reside next to the trivalent (pentavalent) impurities, completing the ideally fourfold bonds at each site.
These charge carriers build up an electric field that opposes the diffusion until the electrostatic force due to the static charge carries is in equilibrium with the tendency to complete the tetravalent bonds that drives the diffusion. In terms of solid state physics one would say that the chemical potential or fermi energy of the two components equilibrates (Fig. 3/4).
However the electrical potential between the two sides is nonzero and one can measure the diffusion potential U_D. It depends on the electron and hole concentration in the two components and is also called off-load potential U_0. Typical values lie between 0,5 to 0,7 V.
Photons can create electron-hole pairs that are separated by the electric field. Electrons are pulled into the n-type, holes into the p-type component. Recombination of electron-hole pairs can happen over a load because the resistance of the semiconductors, cables and the load together is lower than the resistance of the interface between the p- and n-region.
A thin interface allows only for small electron-hole production rates, a thick interface weakens the field separating the charge carriers. Absorption of photons not only happens at the interface but also in the top level p-layer (Fig. 1) and the electron-hole pairs there recombine quickly which lowers the efficiency of the solar cell considerably. Therefore the p-layer should be very thin to allow as many electron-hole pairs to recombine over the load instead of doing this within the p-layer.

2 Temperature dependence

The current density *j,* i.e., the current per unit area, depends exponentially on the temperature *T*:

$$j = \text{const.} \cdot e \cdot \exp\left[\frac{eU}{kT}\right] \qquad (1)$$

e: elementary charge
U: potential applied to the p-n-interface
k: Boltzmann constant

The constant of proportionality depends on the equilibrium concentration of electrons (n-side) and holes (p-side), the diffusion constant and the thickness of the p-doped layer.
When the cell is short-circuited (e.g. over an amperemeter), formula (1) simplifies to

$$j_{kurz} = e \cdot g, \qquad (2)$$

where *g* is the number of electron-hole pairs that are generated per unit area and per unit time. The short-circuit current density j_{short} is therefore proportional to the intensity of the incoming light. g is

weakly temperature dependent (less than 0,01% per K). When the cell is not under load, e.g. when U is measured with a highly resistant voltmeter, U approaches U_0. In this case the temperature dependence is determined by the equilibrium concentration n_0 of electrons and p_0 of holes.
For small temperature changes one can apply a linear approximation by which the off-load potential $U_0 \approx U_D$ changes with increasing temperature typically by 2,3 mV/K.

3 Light sources

Exposition of a solar cell to sunlight will produce a different characteristic curve than in case of a light bulb. However the effects of shadowing and changes of intensity are the same. The characteristic curves depend on the spectral composition of the incoming light.

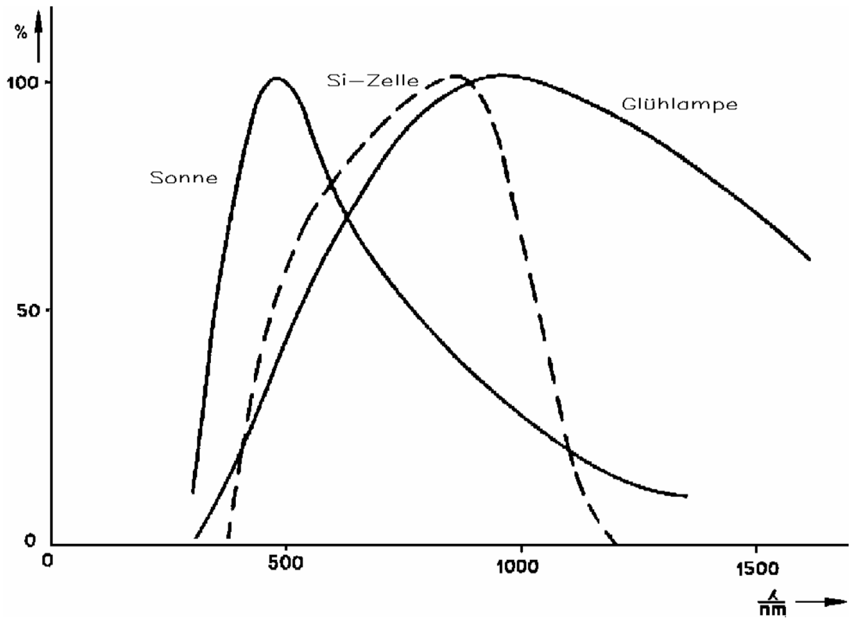


Fig. 4: Spectra of the sun and a light bulb in comparison to the spectral sensitivity of a silicon solar cell.

4 Experimental procedure

1 a) Determine the electric power of a solar as a function of the load resistance. For this expose the solar cell to a light bulb in distance of 50 to 60 cm. Change the load resistance R_{Load} between 0 and 100 Ω in steps of 10 Ω. The power maximum is expected to appear at smaller loads, therefore use a step size of 2 Ω in the range of 0-12 Ω. To determine the power, measure voltage and current according to Fig. 4.

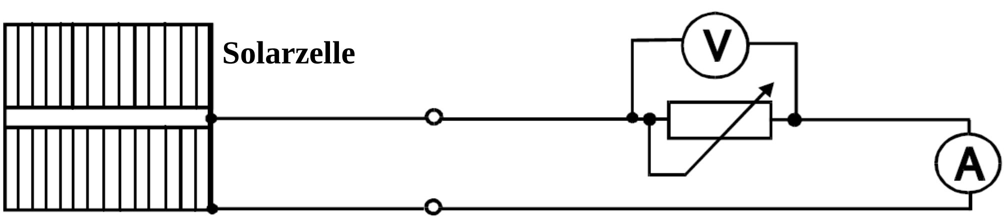


Fig. 5: Wiring for the measurement of a an *I*-*U* curve.

1 b) Examine how the power changes when half of the solar cell is shadowed by the movable plastic cover. Measure voltage and current at R_{Load} = 100 Ω at half and full exposition.

1 c) Another interesting case is zero load resistance. Remove the load and measure firstly the off-load potential U_0 and then the short circuit current I_{short} with the same meter. The solar cell should be fully exposed to the light source.

1 d) Repeat 1 c) but cover half of the solar cell with the plastic cover.

1 e) Repeat 1 c) at lower light intensity (use the dimmer).

2 a) Intensity dependence:
Vary the light intensity using the dimmer. Measure in a range of intensities with 10 steps of equal length. At each intensity determine U_0 and I_{short} with. Estimate the intensity with a thermopile. The intensity is proportional to the voltage at the thermopile. Consider that the thermopile has a characteristic settling time, therefore note down the voltage after an arbitrary exposition time (e.g. 15 s) that is approximately the same for all the intensity measurements.

2 b) Spectral sensitivity:
In the unlikely case that the sun is shining, measure U_0 and I_{short} under sun exposition.

2 c) Temperature dependence:
Cool down the solar cell with 2-3 puffs of ice spray through the inlet on the right side to about -50 °C. The exact temperature is not relevant. Measure U_0 and I_{short}.

3 a) For practical purposes many solar cells are connected. Determine U_0 and I_{short} for 4 different cells.

3 b) Put
- the **3 cells** with the highest power
- all **4 cells**

in series and in parallel and determine P again from U_0 and I_{short}. Make a table!

Notes on the setup:

- There are two mounting parts on the optical bench one of which holds the lamp. The brightness of the light can be adjusted by a dimmer. The other mount can carry either the solar cell or the thermopile.
- The distance between the lamp and the solar cell should be roughly 50 to 60 cm.
- For tasks 1) and 2) use a single solar cell that can be shadowed by a cover. For the other tasks use the four solar cells on the same mount.
- In the discussion of error propagation often times the digital multimeter is mentioned as a main source of error even though it works up to a precision of 1%. Often times the main source of error is a broken cable or the wiring itself.
- „DCA“ means **D**irect **C**urrent in **A**mpere, „DCV“ **D**irect **C**urrent in **V**olt.

5 Evaluation

Regarding 1:

a) Plot power against load resistance. Describe the curve, for which load is the power maximized? What is the efficiency of the solar cell? Determine the light power from the results in task 2 a).

b) How does the power change from full exposure of the solar cell to partial exposure? Explain the result.

c) When $P_{\text{max,theoretical}} = I_{short} \cdot U_0$ is assumed we can estimate the maximal power of the solar cell. Compare to the experimental value of P_{max}! Calculate the relative discrepancy:
$D_{\text{relative}} = (P_{\text{max,theoretical}} - P_{\text{max}}) / P_{\text{max}}$

d) Compare and comment on the results from tasks 1 c) bis 1 e). Make a table.

Regarding 2:

a) The thermopile allows to estimate the light power P_{Light} that reaches the solar cell:

$$I_{\text{Light}} = P_{\text{Light}} / A$$

I_{Licht}: Intensity
A: Area

The active diameter of the thermopile is 25 mm. When the incoming light power is 1 mW, the output voltage is 0,16 mV. The area of the solar cell is $2{,}25 \cdot 10^{-3}$ m². Plot the power of the solar cell ($P = I_{short} \cdot U_0$) against the light intensity.

b,c) Compare the results with those from task 1 c).

Regarding 3:

Determine the power values and compare. Which setup is favourable: Parallel or serial wiring? Are all cells equivalent? What do you conclude?