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innovative Solarsysteme für Schule und Ausbildung
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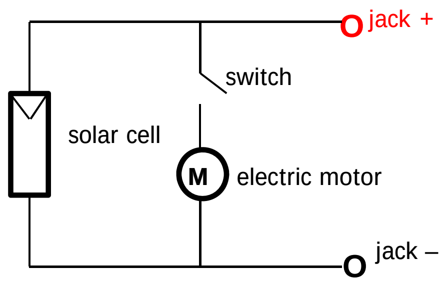
Experimentation manual for the solar module SUSE CM315

Learning station C1

Required materials for all experiments: Solar module SUSE CM315, digital multimeter, 4 lab wires, solar radio SUSE 4.36, LED module SUSE 4.15, cell phone charging module SUSE 4.17, halogen spot light 120 W with switchable desk socket, overhead projector, SUSE solar vehicle 1 or 4

1. Info and energy conversion Page 1
2. Electric voltage Page 2
3. Electric current Page 3
4. Electric power Page 4
5. Quality of the solar cell Page 4
6. Series connection of solar cells Page 5
7. Determination of the efficiency factor of solar cells Page 7
8. Measurement of the irradiance (Light intensity) Page 7
9. Info on the function of a solar cell Page 9
10. 20 test questions Page 10

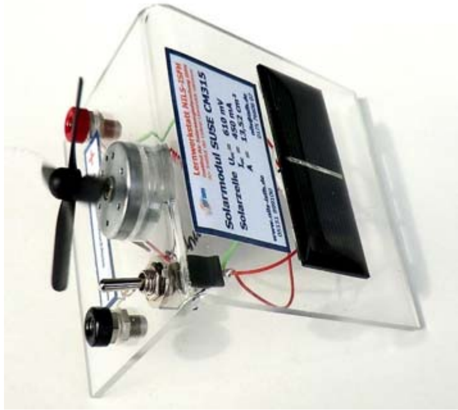


The electric circuit of the solar module

1. The **solar module SUSE CM315** is a **beginner's module with a high-quality solar cell SUSEmod5 52x26 mm in a solar module (laminated module) 60x30 mm.**

Lab wires can be connected to the jacks to connect a multimeter or additional devices, here the solar cell voltage and the short-circuit current can be measured. The solar module is easily assembled and can be applied with multiple experiments to demonstrate photovoltaics (conversion of light radiation to electric energy). With the switch the solar motor can be turned off or on.

The solar module SUSE CM315



Possible light sources for the experiments are:

- direct sunlight (bright sunshine or clouded sky)
- the light on the glass plate of a powerful overhead projector
- the light of a floodlight (halogen spot light 120 W)

Electrical and mechanical data of the solar cell and the solar module:
Solar cell: Dimensions 52 x 26 mm
Solar module: Dimensions 60 x 30 mm
Open circuit voltage V_{oc}: 0.62 V with an irradiance of S = 1000 W/m² = bright sunshine in the summer
Short-circuit current I_{sc}: 0.45 A with an irradiance of S = 1000 W/m² = bright sunshine in the summer

With the self-constructed device energy conversion processes can be demonstrated in a solar module with solar cell, electric motor, and propeller.

After the self-construction of the solar module the solar cell is **held into light radiation for a first test (natural sunlight or the light of halogen spot lamps)**.
If the device was build without fault, the propeller rotates quickly and produces an air stream.

Here several energy conversion processes run down, edit the following **„energy boxes“** and fill them with your **own text.** If the space doesn't suffice, you can complete it on the back.

Light Energy form Characteristics of the energy form light

Solar cell Energy converter Energy conversion process in the solar cell

Electric motor Energy converter Energy conversion process in the electric motor

Propeller Energy converter Energy conversion process by the propeller

The experiments with the solar module SUSE CM315

2. The electric voltage of the solar cell

The open circuit voltage V_{oc}
V_{oc} is the electric voltage V of the unstressed solar cell, no device is connected to the solar cell. The measurements take place in bright sunshine or in front of a halogen spot light or on an overhead projector with S = 1000 W/m², Motor turned off!

The value of the voltage V_{oc} should be **between 0.58 V and 0.62 V in the sunlight**, **with clouded sky 0.5-0.55 V**, **indoors approx. 0.3 V**, *independent of the area*! With the same irradiance all solar cells should have roughly the same voltage, the standard test value being 0.62 V. Small differences are due to quality differences.

The open circuit voltage only depends on the *light intensity*, the *material*, and the *quality* of the solar cell. With our solar cell the material is silicon Si.

Use a multimeter in the measurement range 20 V DC and connect the voltmeter with the right polarity to both jacks of the illuminated solar cell with 2 lab wires.

Measurements on the voltage: without solar motor = motor turned off

Measurement site	Outdoors with bright sunshine adjusted towards the sun or on OH projector	Outdoors with sunshine in the shadows	Outdoors with clouded sky	Inside a lit room
Open circuit voltage V in V with Solar-Motor				
Open circuit voltage V in V without Solar-Motor Motor turned off				

3. The maximum current of a solar cell = short-circuit current

The short-circuit current I_{sc} of the solar cell

In contrast to other power supplies (battery, power supply unit,...) solar cells may be short-circuited, the **short-circuit current actually is a very important value for solar cells. The current flows directly from the** solar cells negative pole over the amperemeter to the positive pole here.

For measuring the current use a multimeter in the measurement range of 10 A DC, that is connected to the + and – jacks of the solar cell. Only for measurements indoors use the measurement range 20 mA or 2 mA!

The value of the short-circuit current is ***directly proportional to the cell area and the light intensity***/irradiance, as well as dependent on the quality. Standard test value: With a solar cell of this module with the dimensions 52x26 mm the short-circuit current is exactly **0.45 A = 450 mA** with a light intensity of 1000 W/m².

Additional measurements:

Measurement site	Outdoors with bright sunshine adjusted towards the sun or on OH projector	Outdoors with sunshine in the shadows	Outdoors with clouded sky	Inside a lit room
Short-circuit current I_{sc} in A and in mA **with solar motor**				
Short-circuit current I_{sc} in A and in mA **without solar motor**				

What do you notice in the voltage and current measurements? Note your observations/explanations here:

4. The electric power of the solar cell P_E in W (Watt)

$P_E = V_{oc} \times I_{sc} \times 0.8 =$.................W

The factor 0.8 arises from the I(V) and P(V) characteristic curves of the solar cell and can be determined exactly in an experiment for higher Secondary School levels with the solar module SUSE 5.15.

No new measurements necessary, calculation with the two already determined values V_{oc} and I_{sc}

Simplified approach: P is open circuit voltage x short-circuit current x 0.8, so P should be **0.22 W in the ideal conditions** with an irradiance of **1000 W/m²** (The factor 0.8 arises from the characteristic curves and the MPP of the solar cell).

Additional calculations: (Motor cut off or turned off)

Measurement site	Outdoors with bright sunshine adjusted towards the sun or on OH projector	Outdoors with sunshine in the shadows	Outdoors with clouded sky	Inside a lit room
Short-circuit current I_{sc} in A Transfer values				
Open circuit voltage V_{oc} in V Transfer values				
Power P $V_{oc} \times I_{sc} \times 0.8$ **in W**				
Power P $V_{oc} \times I_{sc} \times 0.8$ **in mW**				

5. The quality of the solar cell

= current density j in mA/cm²

Very good: > 40 mA/cm²
Good: 32- 40 mA/cm²
Medium: 24- 32 mA/cm²
Bad: < 24 mA/cm²
With an irradiance of 1000 W/m² !!

Maximum possible theoretical value: 45 mA/cm²

The **current density j** (in mA/cm²) specifies, how much current a **1 cm² piece of solar cell** produces, the more, the better! **For that purpose the irradiance has to be exactly 1000 W/m²** (international standard value = bright sunshine or OH projector), because with a lower irradiance <1000 W/m² the current density j of course is also lower!

$$j = \frac{\text{Short-circuit current in mA}}{\text{Cell area in cm}^2} = \text{............mA/cm}^2$$ **with irradiance 1000 W/m² !**

The current density of the used cell is..........................mA/cm²

The quality of the solar cell is...

Very good – good – medium- bad

Type of the solar cell in the solar module: Please encircle cell type

monocrystalline solar cell – polycrystalline solar cell

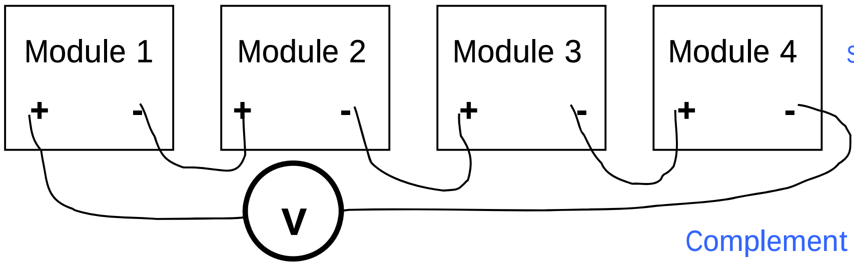
Explain the composition and the differences between these two cell types (Internet or NILS-ISFH-PV compendium).

6. Series connection of solar cells

Solar cells can be connected in series in any number to reach higher voltages!
In photovoltaic technology there are most often 36…72 solar cells connected in series in the big solar modules.

Several modules SUSE CM315 in series connection:

Place the modules in the sunlight or (with the upper surface facing down!) on an overhead projector and connect the modules in series (as shown in the drawing).
Of course you can also connect more than 4 modules in series, with 6 solar cells in series connection you can already operate a 3V radio! Try it!



Series connection of 4 modules

Complement the table at the bottom, if you connect more than 4 modules in series!

Single module	V_{oc} in V	I_{sc} in A
1		
2		
3		
4		

Values for the series connection of ………. modules:

V_{tot}=…………………………V

I_{sc} =……………………………A

What do you notice? Describe and explain!

Explain the series connection here! Draw a circuit diagram with 4 solar cells:

Develop a series connection of <u>6 solar modules</u> and connect the following devices:
A) a solar radio SUSE 4.36
B) an LED module SUSE 4.15 red or green or/and rainbow

Test the function of the radio / the LED module with the 4 possibilities:
a) outdoors
b) on the OHP
c) in front of a halogen spot lamp
d) in a lit room

Note the results here and explain:

Additional experiments:

1) Connection of a cell phone charging device to 14-20 solar cells in series connection with DC- DC- converter SUSE 4.17

2) Charging of an energy storage and subsequent driving of the SUSE solar vehicle 1 or 4 with 2-max. 4 solar cells in series connection

7. Determination of the efficiency factor of a solar cell

Requirement: Overhead projector or sunlight with an irradiance of 1000 W/m²

1. Conversion of the light power 1000 W/m² or rather 0.1 W/cm² to the real area of the solar cell:

   The cell as an area of 13.52 cm², it receives from 1000 W/m² a <u>light power</u>

   P_L :................. W

2. The electric power from exercise 3 was with the measured cell:

   P_E =..................W

3. Electric power P_E : light power P_L * 100 = Efficiency factor in %

$$\text{Efficiency factor} = \frac{P_E}{P_L} * 100 = \text{.............................}\%$$

The efficiency factor of the used solar cell is.............................%.
Efficiency factors of solar cells:

Monocrystalline cells: 17- 21 % Polycrystalline cells: 12 – 19 %

The used solar cell was a...cell.
Monocrystalline / polycrystalline

Its measured efficiency factor was:...
very good – good – medium - bad

8. Measurements of the light intensity (irradiance S) in W/m²

With the calibrated solar cell used here the light intensity in W/m² can be determined exactly, because the short-circuit current is proportional to the light intensity = irradiance S.

1000 W/m² is the intensity of the light radiation of the sun with cloudless sky in the summer and the international standard measurement value for solar cells.

Short-circuit current I_{sc} of the solar cell with an irradiation of 1000 W/m²

I_{SC}= ....0.45...................A = ...450................mA

Measurement of the irradiance S of light (light intensity) in W/m²:

Because the short-circuit current I_{sc} of a solar cell is proportional to the irradiance S, it holds:

$$\frac{I_{sc} \text{ in A}}{1000 \text{ W/m}^2} = \frac{I_{mes} \text{ in A}}{S_x \text{ in W/m}^2}$$

or solved for S_x:

$$S_x = \frac{I_{mes} \text{ (in A)} * 1000 \text{ W/m}^2}{0.45 \text{ A}}$$

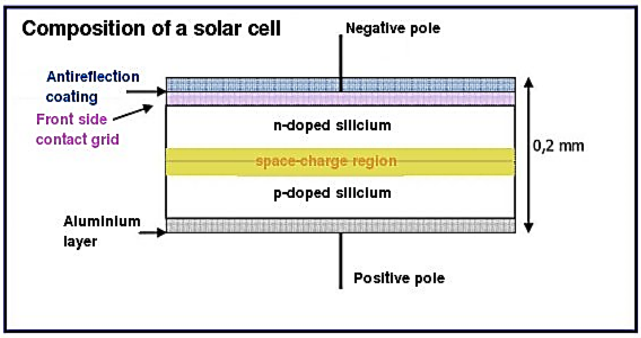
It is:
I_{sc} in A: The calibrated short-circuit current at 1000 W/m² **= 0.45 A**
I_{mes} in A: The measured short-circuit current at the irradiance S_x
S in W/m²: The measured irradiance of the light radiation

Measurements outdoors and with light sources:

Light radiation	**Short-circuit current I_{sc} in A**	**Irradiance S_x in W / m²**
Bright sunshine, measured directly towards the sun		
Bright sunshine, measured in the shadows		
Clouded sky		
Very gloomy weather		
On the plate of an overhead projector		
10 cm **above the surface** of an overhead projector		
40 cm in front of halogen spot lamp 35 W (Spot light SUSE 5.16)		
40 cm in front of halogen spot lamp 150 W		
Indoors, directed towards the window		
Indoors, directed towards the ceiling		

What do you notice? Explain here:

Composition and function of a silicon solar cell II from class level 8/9 upwards (ISCED-level 2 and 3)



A solar cell is a large-area silicon semiconductor diode, the **n-doped layer is the surface** of the solar cell, here the light gets in, the blue coloration is due to the **transparent** (!) thin antireflection coating. **The n-doped layer is the negative pole of the solar cell!** The thin silver conductors serve as electrical conductors for the take-up of the current. **The p-doped layer is the lower surface (bottom side) of the solar cell**, normally it is coated razor-thin with aluminium therefor looking grey. Deposited silver conductors serve for the soldering of wires. Here the **positive pole of the solar cell** is located. **The internal photoelectric effect of separation of charges occurs at the p-n-junction.**

1. Electric voltage U

A solar cell provides a **typical voltage of 0.55 – 0.61 V** in open-curcuit mode (= voltage without a connected consumer load).The exact value of the **open-circuit voltage** depends on the material of the semiconductor, the doping, the temperature, and the irradiance S, but **not on the area**.

The open-circuit voltage does not depend on the area of the solar cell and (over a certain threshold) just slightly on the light's intensity.

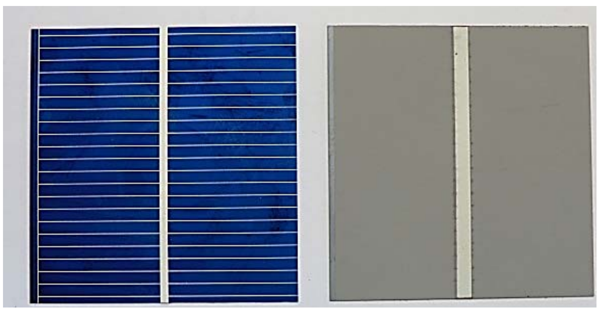
2. Electric current I

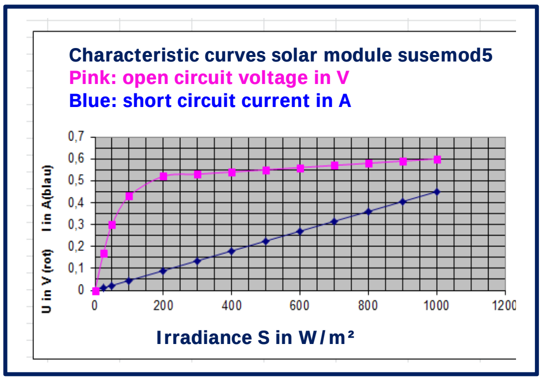
The maximum electric current I (= short circuit current) that a solar cell can provide depends on 2 factors:

- **Area of the solar cell** : The bigger the area the bigger is I (proportional)!
- **Intensity of the incoming light radiation:** The higher the light's intensity S, the higher is I (proportional)!
- Quality of the solar cell (very good solar cells: I = 36 - 40 mA/cm²!)

The **cause of the current** are the **free electrons generated by incoming light quanta** in the junction layer (p-n-junction) per time unit. Because of the internal electric field they diffuse to the (n-doped) surface of the solar cell and from there they arrive at the (p-doped) lower surface through the external circuit. This process is called **"internal photoelectric effect"**, explained by Einstein 1905.

If current is extracted from the solar cell the voltage U decreases. The exact linkage between voltage and current is shown in the U-I characteristic diagram of a solar cell as explained in the level III file. The **maximum power** is only reached in one certain point, viz. at a certain discrete voltage and current, this point is called **MPP = maximum power point**, important in practice! The **efficiency factor of a solar cell** is about **15-20%**, viz. only 15-20% of the incoming light is transformed into energy, depending on the solar cell type.





Left-hand side: The U(S)- characterization diagram (pink) and the I(S)- characterization diagram (blue) of the SUSE solar cell in the module susemod5.
The irradiance S is the light intensity in Watt per m², 0 meaning absolute darkness, 1000 meaning bright sunshine with blue sky in the summer half-year.

Top left: The top side of the SUSE solar cell 52 x 52 mm with a thickness of 0.2 mm. The blue coloration is the (transparent!) antireflection layer, the bright lines (pure silver!) are electrical conductors, the front side contact grid is the negative pole of the solar cell. On the wide line cell connectors or cables can be soldered. Beneath the blue layer the silicon crystals are visible.

Top right: The lower surface of the SUSE solar cell 52 x 52 mm. The grey layer is the metallic back side, pure aluminium, the positive pole of the solar cell. Because aluminium can not be soldered, a silver stripe to solder cell connectors or connection cables is plated.

20 questions on the solar module and the experiments class level 8 and higher

Easy
Medium
High level

1. What material do solar cells consist of?
2. Which energy conversion takes place in a solar cell?
3. Why are solar cells blue on the front side and gray on the back?
4. What do the many thin lines on the front of the solar cells mean?
5. Where are the electric poles of the solar cell?
6. How big is the electric voltage of a solar cell with an irradiance by sunlight with bright sunshine? (S = 1000 W/m²)
7. To get a higher voltage, 8 solar cells are connected in series. Draw this connection and state the voltage, if this series connection is illuminated by bright sunshine.
8. How thick is a solar cell?
9. What is meant by "short-circuit current"? Why may a solar cell be short-circuited, but never a rechargeable battery?
10. How can the quality of a solar cell be determined?
11. How can the light intensity (= irradiance S) be determined with the solar cell of your solar module?
12. With gray, clouded sky you measure a short-circuit current of I = 50 mA with your solar cell. How big is the light intensity (irradiance) of the daylight?
13. How big is the efficiency factor of a standard solar cell?
14. A big, square 6-inch solar cell (6 inches = 156 mm) has an open circuit voltage of 0.61 V and a short-circuit current of 8.1 A in bright sunshine. Now it is cut by a laser into 9 equal squares with an edge length of 52 mm. How big are the open circuit voltage and the short-circuit current of a small solar cell?
15. A whole school class with 30 students connects their modules in series and places them in the bright sunshine. How big are the voltage and the short-circuit current of the series connection?
16. You want to charge a smartphone with the self-made solar modules. This device needs a charging voltage of 5 V. How do you have to proceed? Draw a circuit diagram and explain!
17. How big are open circuit voltage, short-circuit current and electric power of your solar cell with clouded sky with S = 500 W/m²?
18. Square solar cells are produced in the dimension of 6 inches. How big is the edge length in mm?
19. 10 solar cells are connected in parallel. What effect does this connection have?
20. Which element is often used for n-type doping, which for p-type doping?

For teachers there are solutions to the questions available via info@sundidactics.de