PH Pädagogische Hochschule Wien

PHOTOVOLTAICS EXPERIMENTS

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ΓΔ Εκπαίδευση και πολιτισμός

GD Bildung und Kultur

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2009

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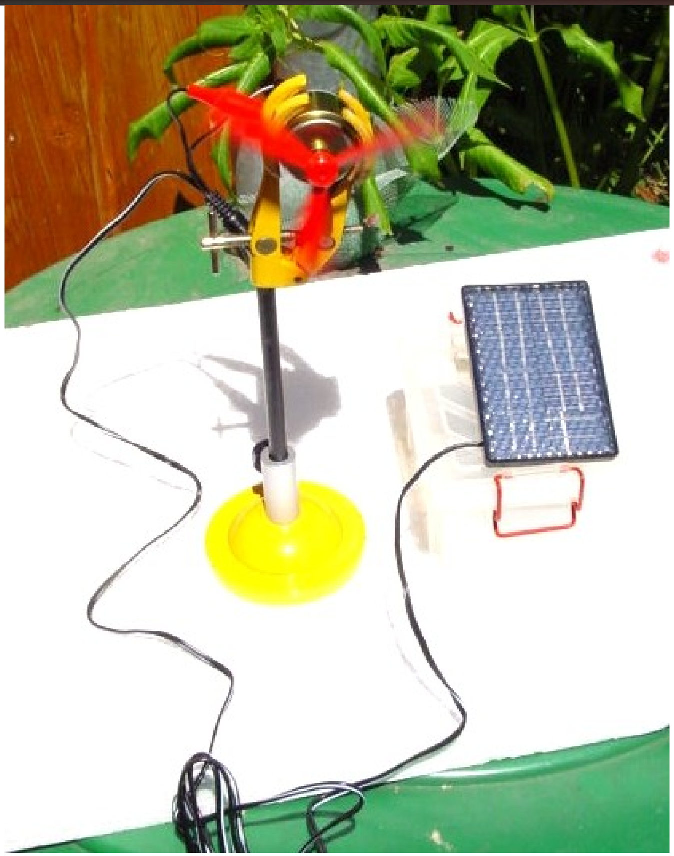
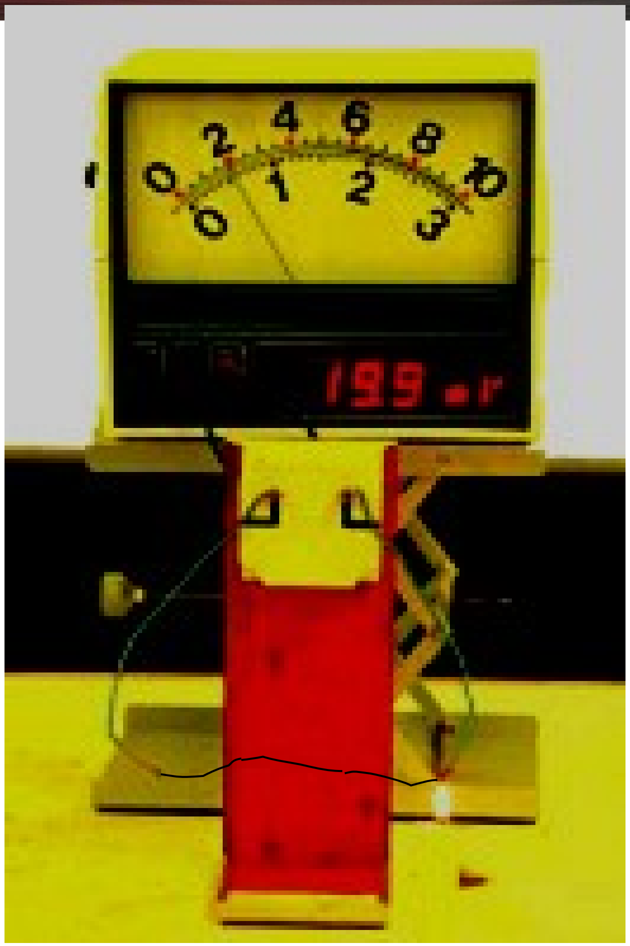
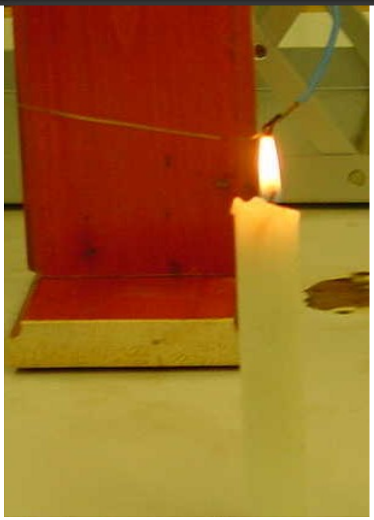
The Sun generates Electricity



Solar Cell at work)

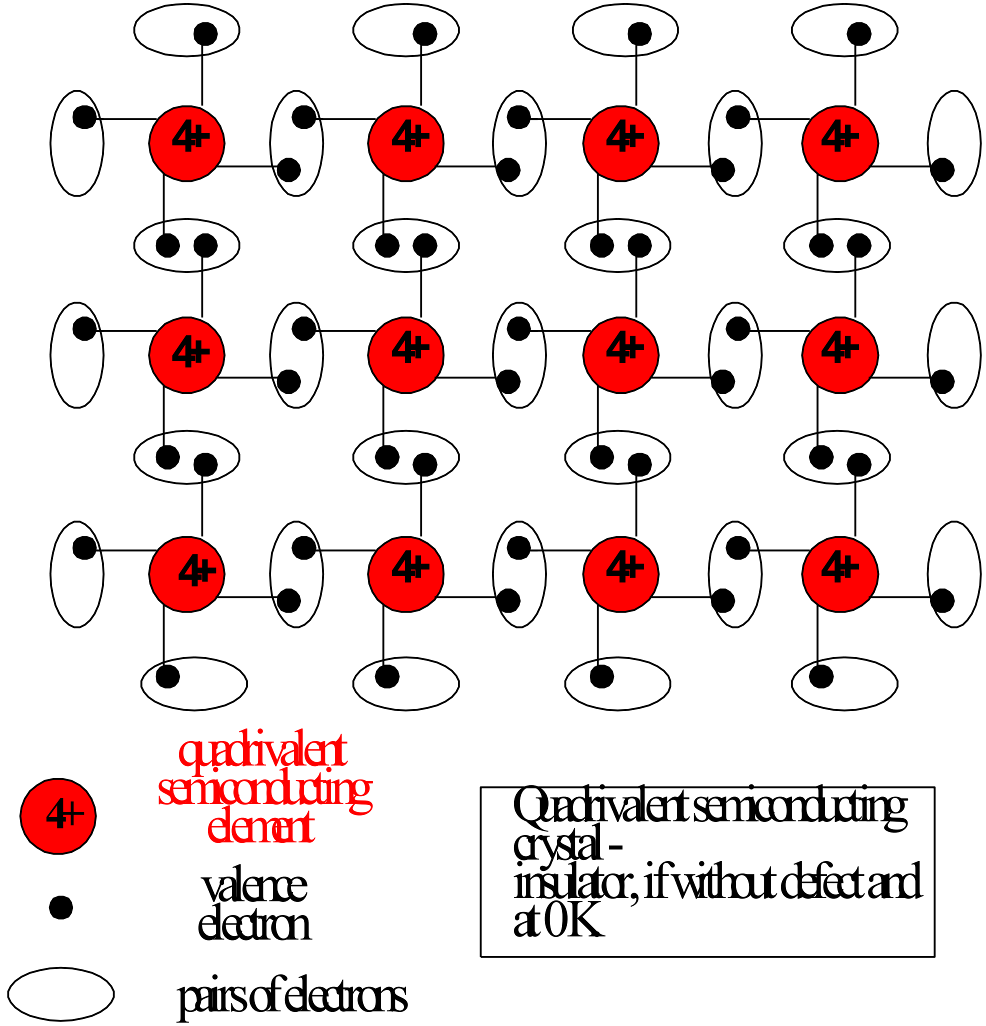




Thermocouple
(Candle instead of
concentrated
sunlight)

intrinsic conduction

traditional schedule

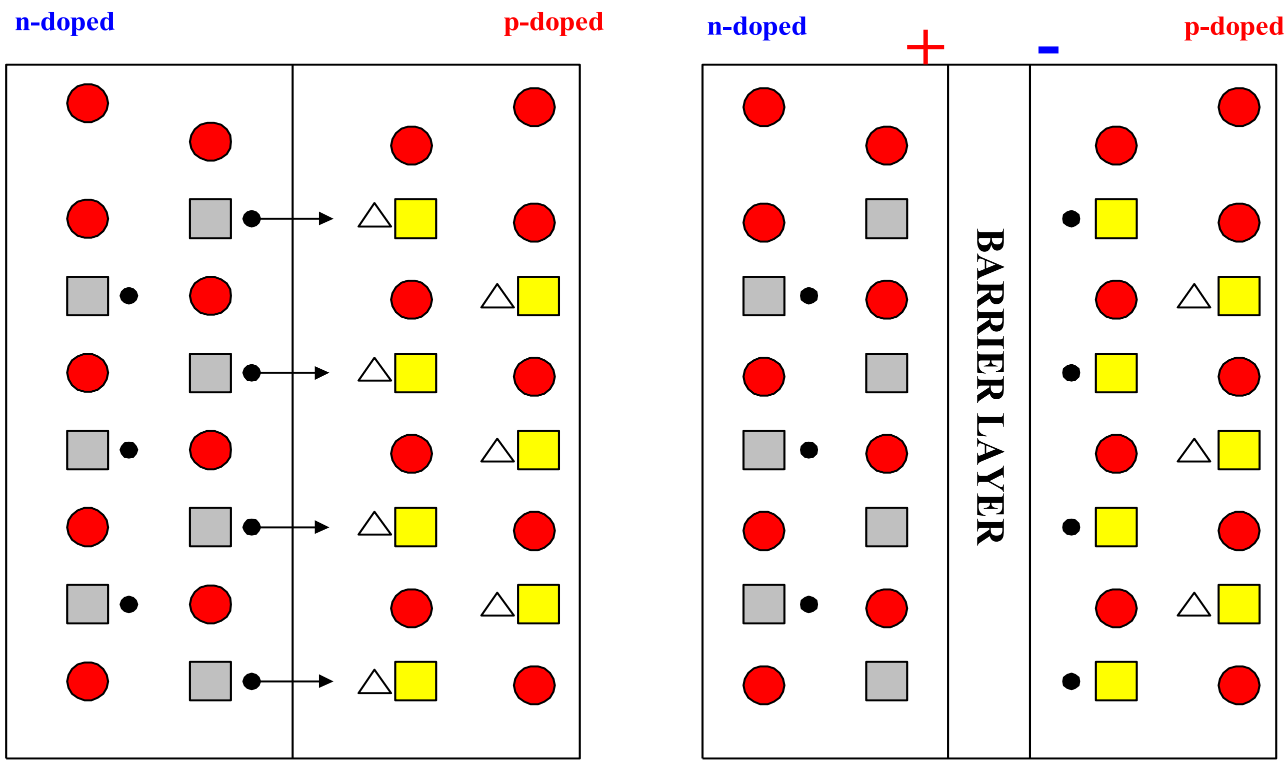


Lattice of the diamond-type
Because of defects in the crystal and
at rising temperature - input of caloric energy -
some electrons are set free -
the crystal shows intrinsic conduction.
Matter: Silicon, Indiumphosphide, Galliumarsenide, Cadmiumtelluride

New: Compounds as III-V or II-VI type or organic compounds

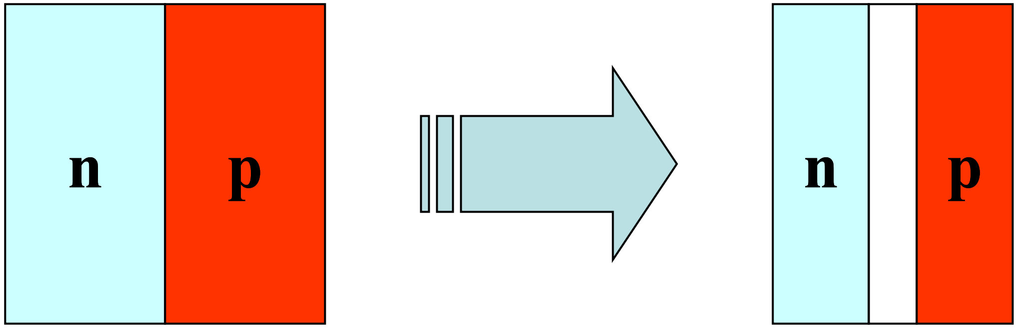
Doped Semiconductors

Electrons move to the defective electron (hole) deficit of electrons excess of electrons



- quadrivalent atom
- trivalent atom
- quinvalent atom
- the fifth electron is not used for binding
- electron hole in the lattice (grid)
- moving direction of the electrons

Doped Semiconductors

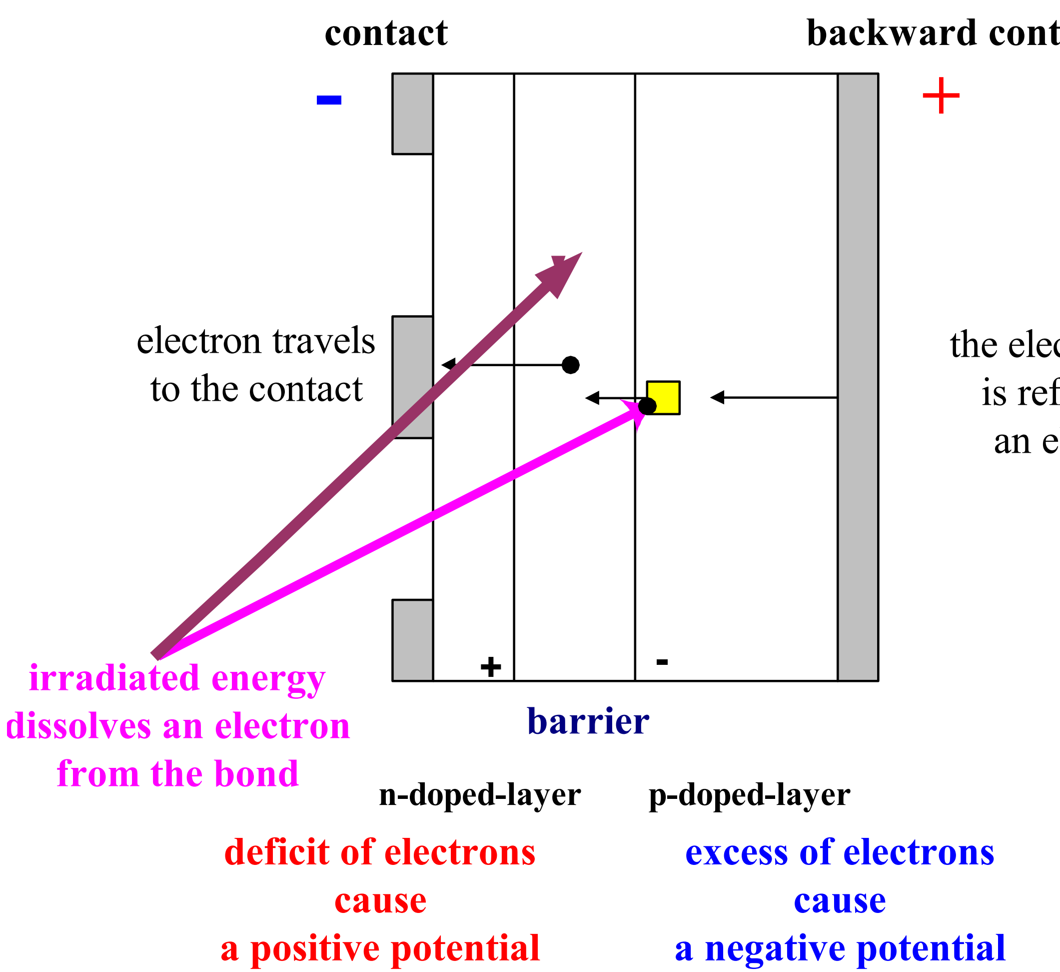


intrinsic (reverse) voltage

There must be:

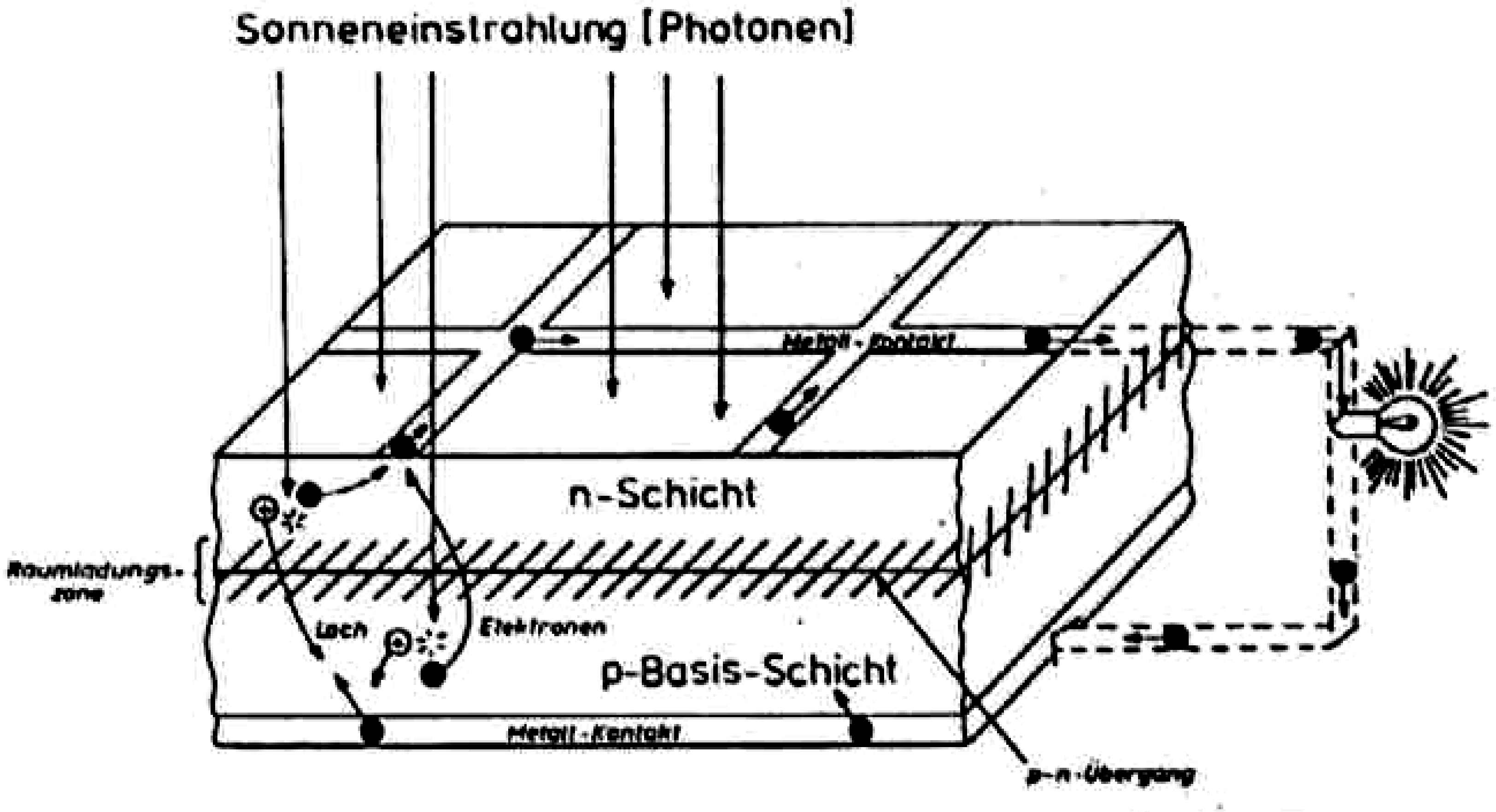
A carrier – usually a crystal grating
n-layer – providing electrons
p-layer – providing places for the electrons on travel

Generation of Photovoltaics



For generating photovoltage, you need:
➯ matter, from which photons are able to dissolve electrons: Si, Ge, semiconducting compounds (InSb, InP, GaAs, GaAsP, CdS, CdTe).
➯ Intrinsic potential difference being able to separate the electrons from the positive defective electrons.

Generation of Photovoltage



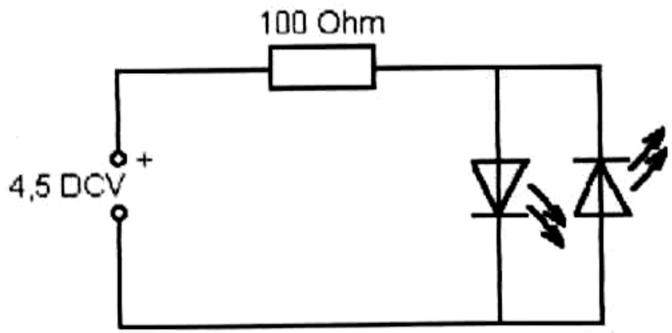
Generation of Photovoltage

The band gaps are:
Si...1,12 eV
maximum of sensitivity: red
long wave limit: IR 1,1 µm
above translucent
Ge...0,7 eV
GaAs...1,42 eV
CdTe...1,5 eV
GeS.....1,5 eV
InSb...0,2 eV (IR)

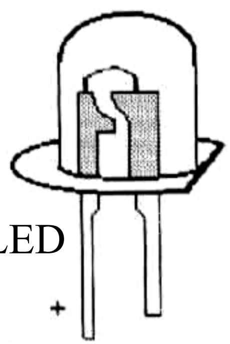
Generation of Photovoltage

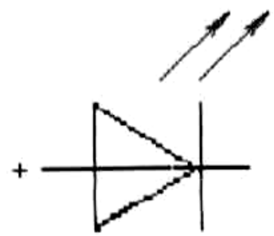
Efficiencies at 1 kW/m²:
c-Si (crystal Si).....max 28 %
practically 18 %
mc-Si (multicrystal-Si)...16 %
a-Si (amorphous Si)...13-17%

The LED - forward and reverse biased



This picture allows you to find out the correct positioning of the LED





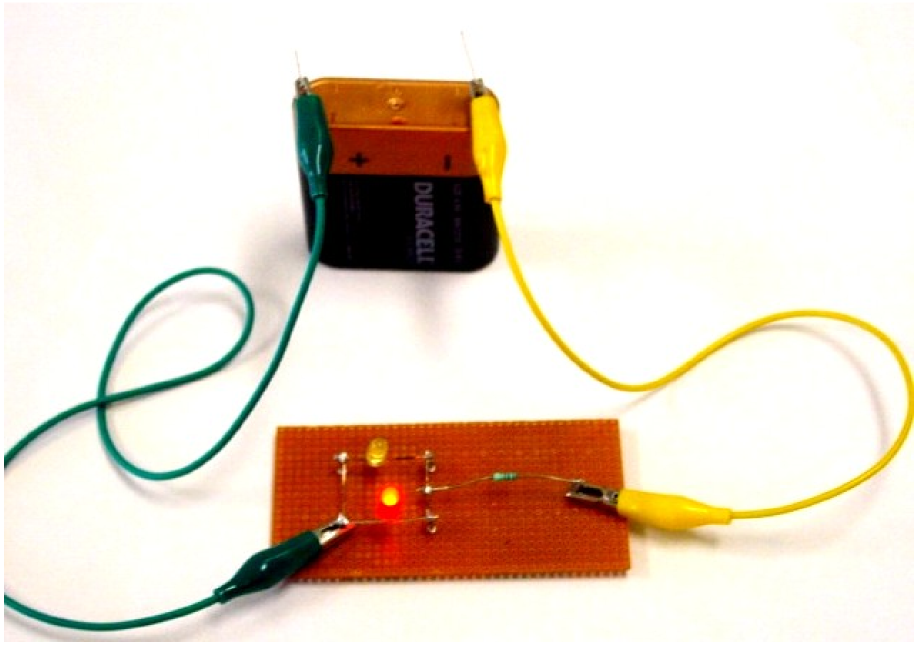
symbol

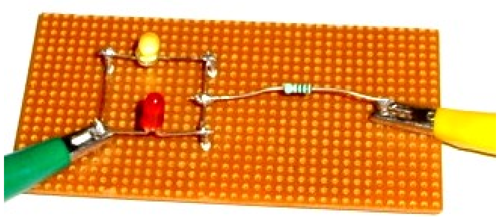
Forward voltage drop...measured at the forward biased lED, necessary to force charges passing the LED

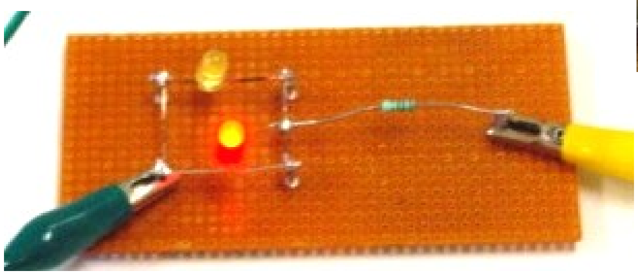
Which of both LEDs is shining ?
Change the poles of the battery (pole reversal).
Which of the LEDs shines now ?

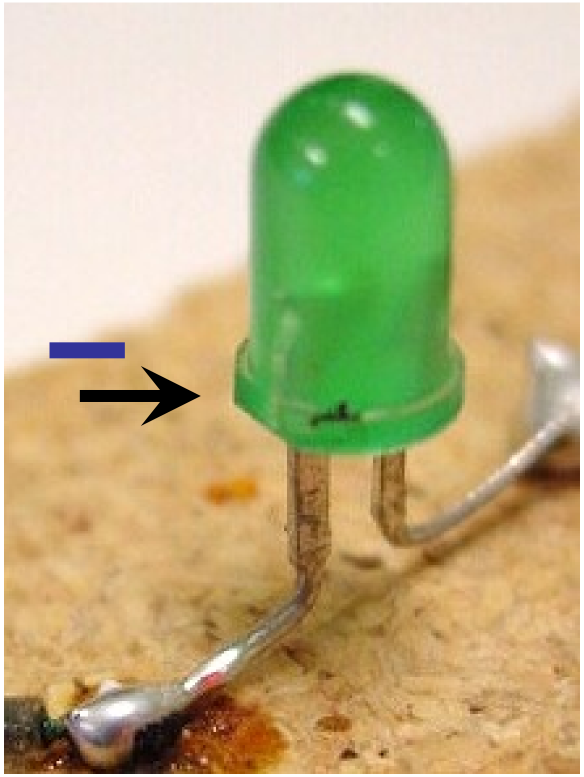
Remove one of the LEDs.
Measure the drop in voltage cross the LED.
The LED is forward biased, it shines:
U = ... V
The LED is reverse biased.
U = ...V
If the LED is reverse biased, a high drop in voltage

is to be found cross the LED.

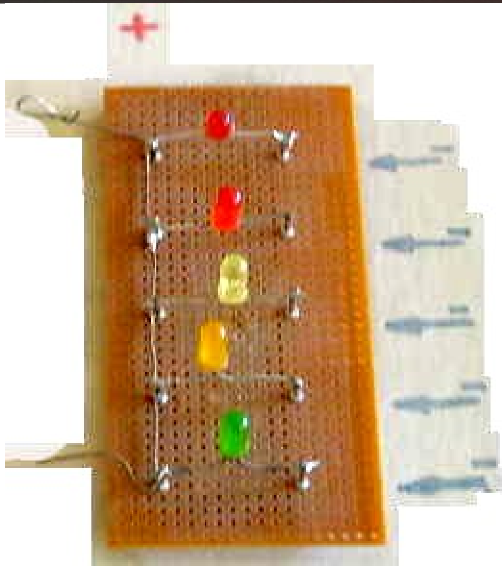

DURACELL



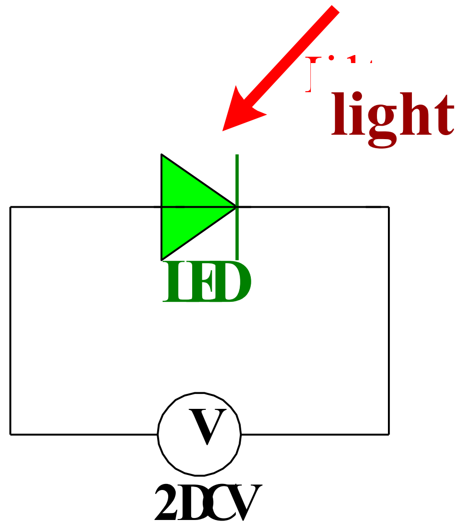


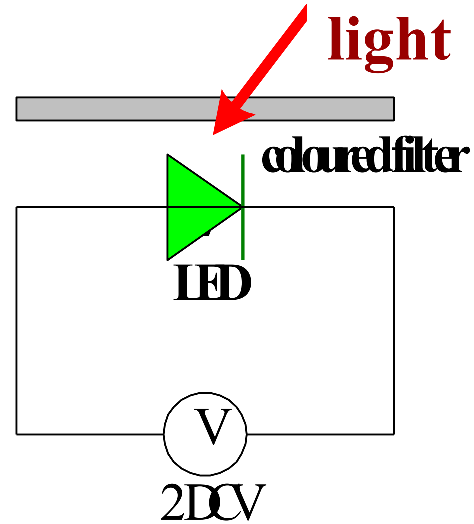


The LED as Photovoltaic Cell



Measurement of the voltage generated by irradiation:





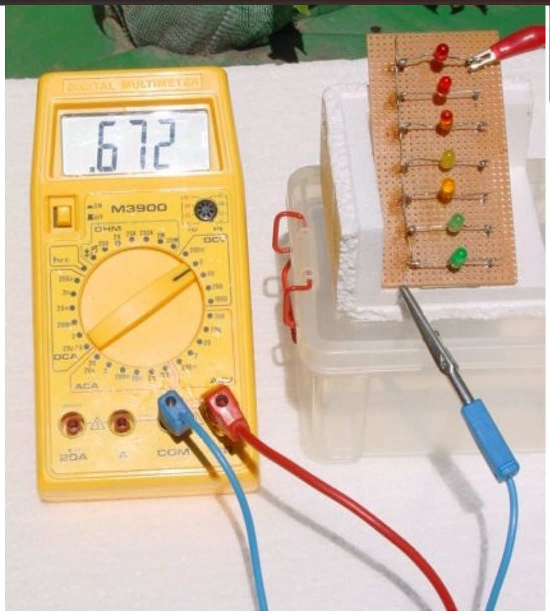
LED red	U=...............V
LED green	U=...............V
LED.............	U=...............V

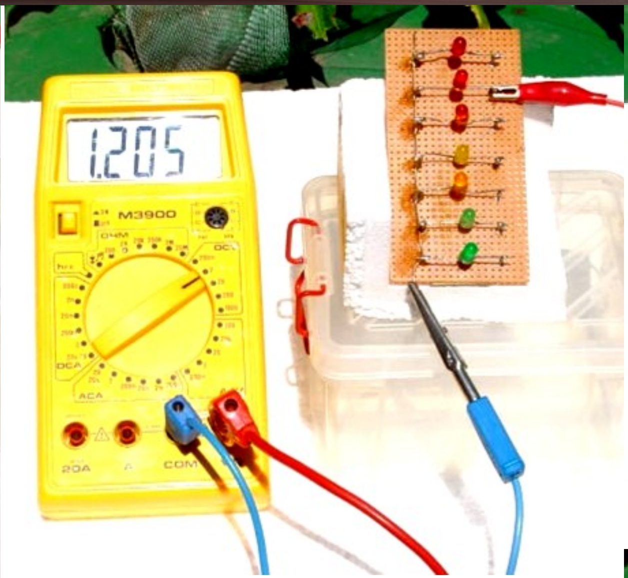
Note, to which part of the spectrum the different LEDs are sensitive.

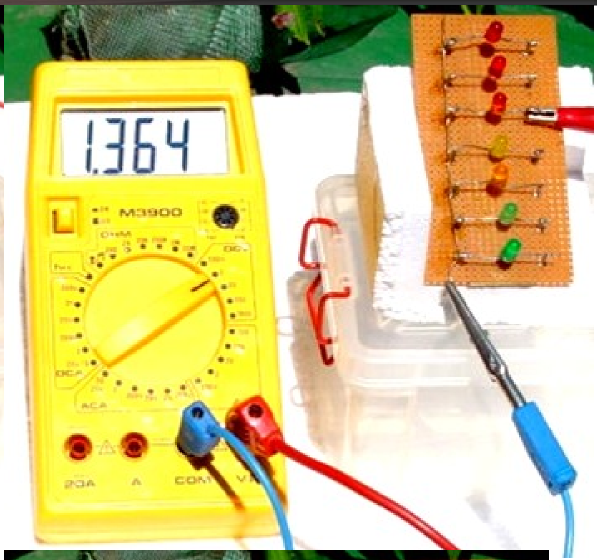
	Filter red	Filter green	Filter blue
LED red	U=.........V	U=.........V	U=.........V
LED green	U=.........V	U=.........V	U=.........V
LED..................	U=.........V	U=.........V	U=.........V

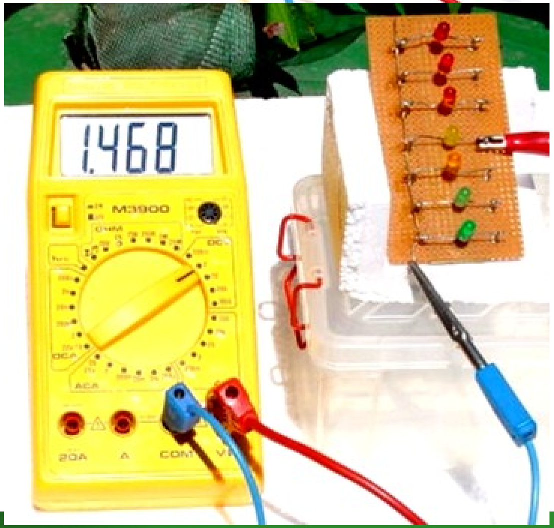
The so generated voltage is called photoelectric voltage.

The LED as Photovoltaic Cell



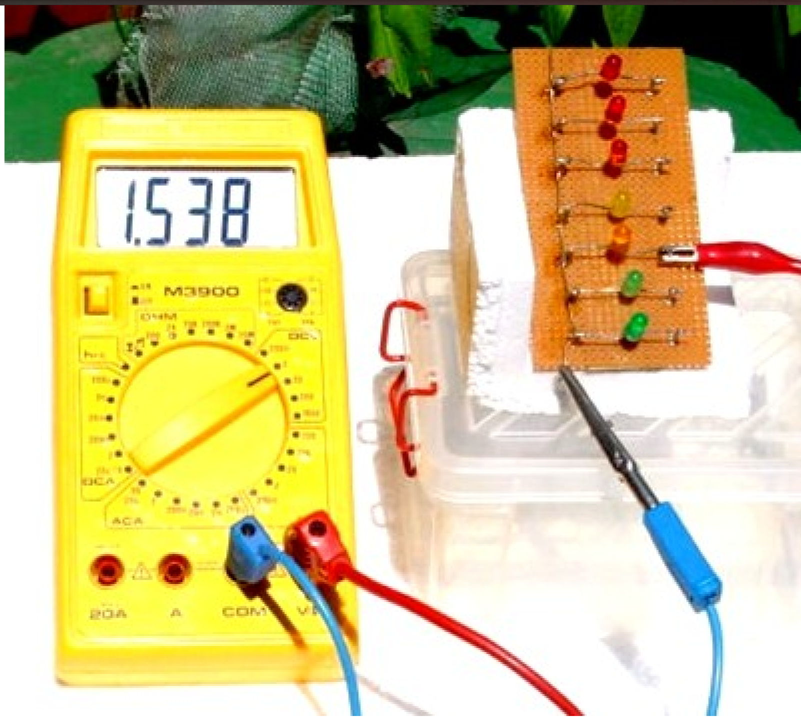


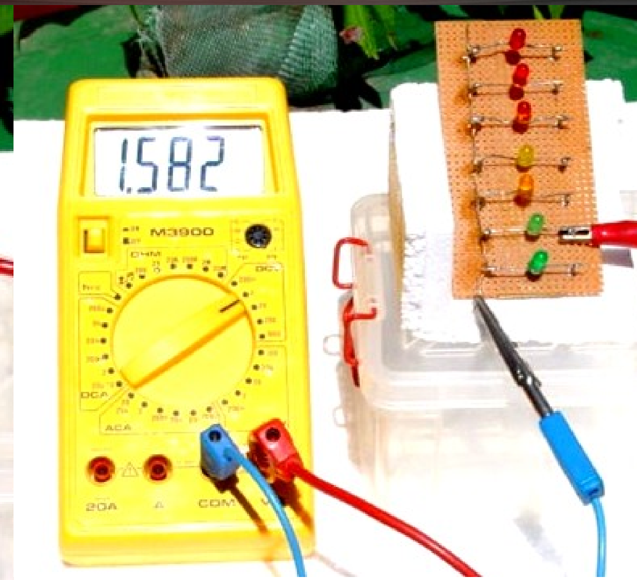


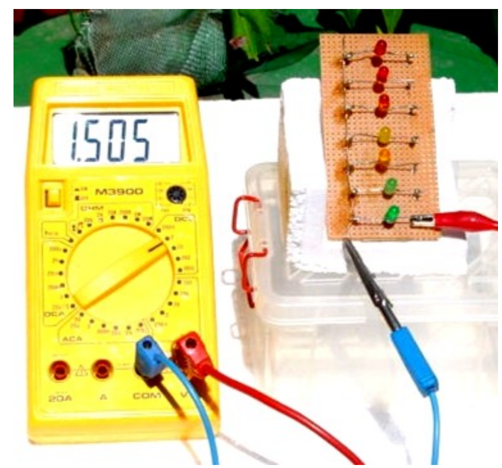


The voltage depends on the gap between conductive and valence band.

The LED as Photovoltaic Cell



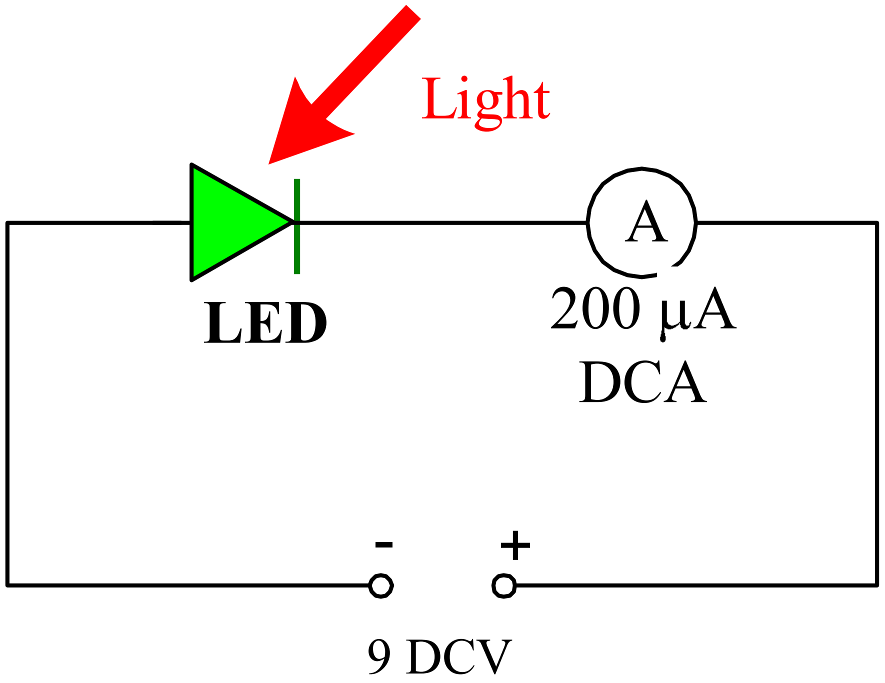




Relatively high Voltage, but...
....about no capacity !!

The LED is used as PHOTODIODE

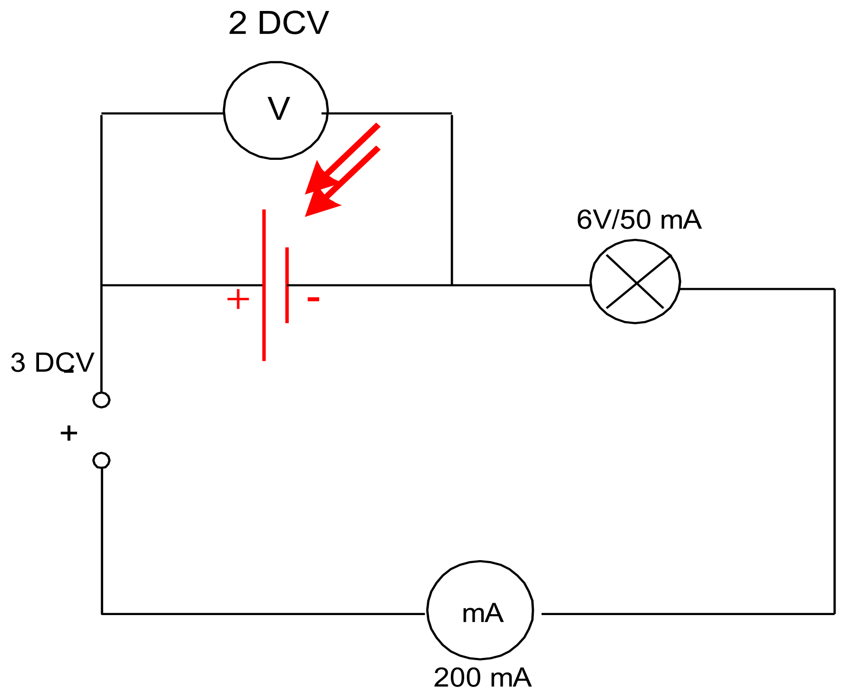
The LED is connected into the circuit reverse biased!!



Expose the LED to an intensive radiation.
The intensity of current is I = ... µA.
Now vary the irradiance only a bit.
In doing this observe the current´s intensity.
The result is:..................................
Application: very sensitive exposure meter

Resistance of a Solar Cell

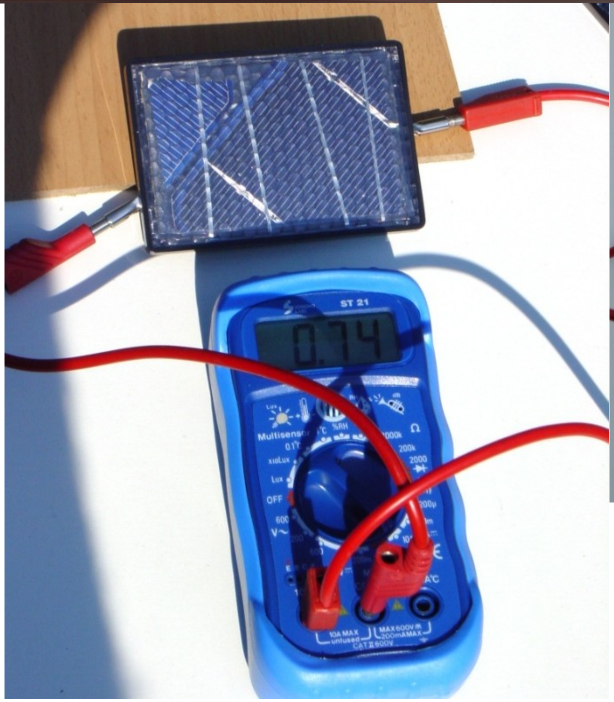
The solar cell is reverse biased. Do not use more than 3 DCV.
Only use a little surface, if necessary cover the surface partially with a cardboard.



If the solar cell is shadowed, it has a high internal resistance because of a high drop in voltage.

	U (V)	I (mA)	R (Ohm)
Solar Cell exposed to daylight			
Solar Cell totally darkened			

Resistance of a Solar Cell



Direct sunshine: U = 0,55V, I = 0,74 A
R = 0,8 Ohm

Shadowed: U = 0,47V, I = 0,067 A

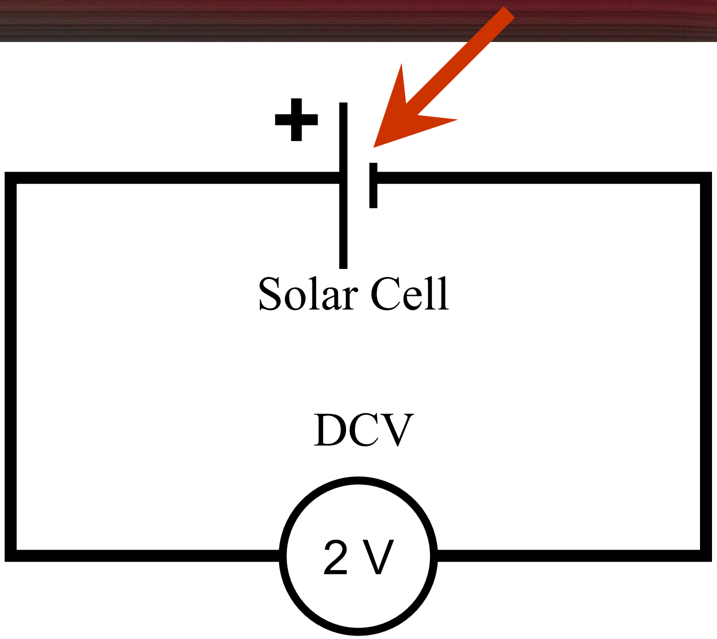
R = 7 Ohm

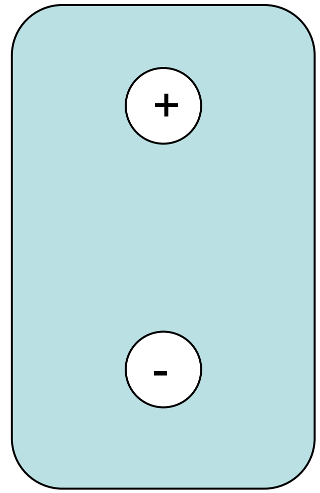
Resistance of a Solar Cell

Solar Cells connected in series, one of them being shadowed →
bypass diode is necessary.

Darkened: U = 0,11V, I = 0,0012 A
R = 92 Ohm

Open-Circuit-Voltage of a Solar Cell





back side
with
connections

	U in V
dim room	
bright room	
shadow	
sun	

The open circuit voltage is measured at different irradiances.

$$U_{max} = \text{...........} \ \mathbf{DCV}$$

	Irradiance	Open-Circuit-Voltage in V
Sun	I = 1040 µA	
Shadow	I = 450 µA	
Indoor	I = 13 µA	

You may draw a diagram now.

Open-Circuit-Voltage of a Solar Cell

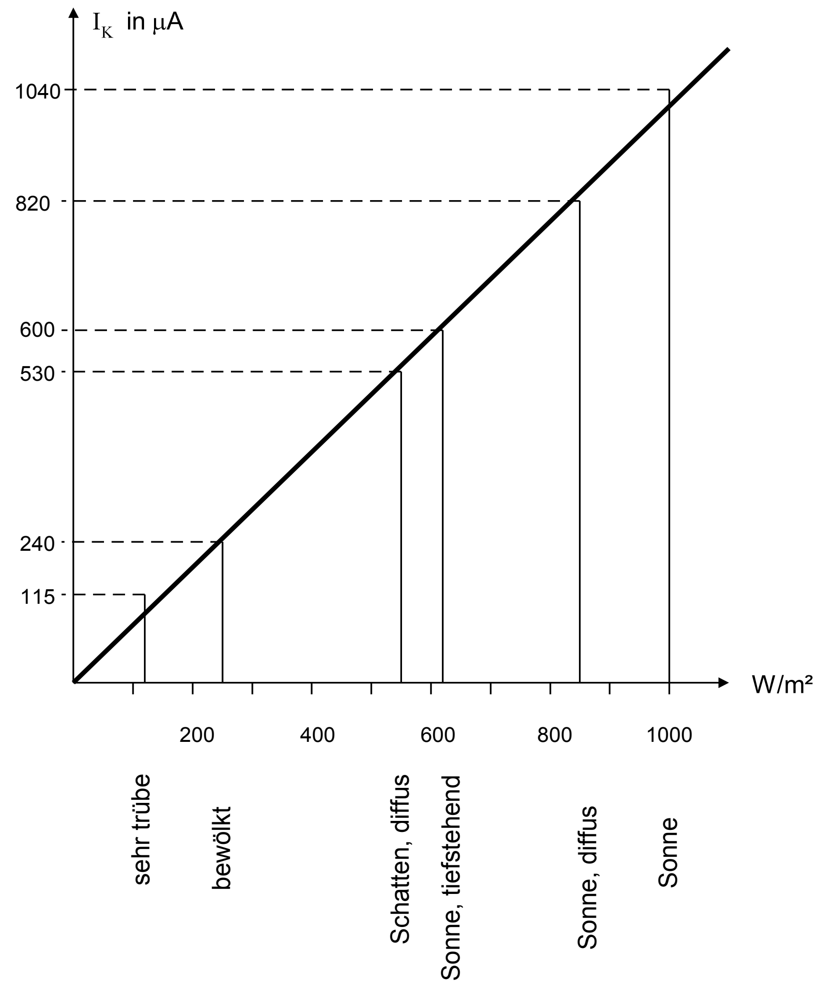
bright sun: U = 0,55 DCV

shadowed: U = 0,47 DCV
(scattered radiation)

darkened: U = 0,11 V
(Infrared radiation)

Calibration for Irradiance-Measurement

OBSERVATION	CURRENT	IRRADIANCE
Sunshine	1040 µA	1000 W/m²
Sun, a bit diffuse	850 µA	820 W/m²
Sun, before dawn	620 µA	600 W/m²
shadow, diffusely illuminated	550 µA	530 W/m²
clouded	200-300 µA	240 W/m²
room, bright	130 µA	125 W/m²
very dull	120 µA	115 W/m²
room close to the window, shadow	60 µA	60 W/m²
room dark	13 µA	13 W/m²



Solar Cell d = 1 cm

Calibration Solar Cell 1 cm² illuminated

Intensity Short Circuit Current	I in µA	Irradiance in W/m²	µA/W.m^{-2}
Sun	1040	1000	1,04
Sun, diffuse	850	820	1,04
Sun, before dawn	620	600	1,03
Shadow, bright	550	530	1,04
clouded	250	240	1,04
Room, bright	130	125	1,04
Outdoor, very dull	120	115	1,04
Indoor close to a windo	60	60	1,00
Indoor, dark	13	13	1,00

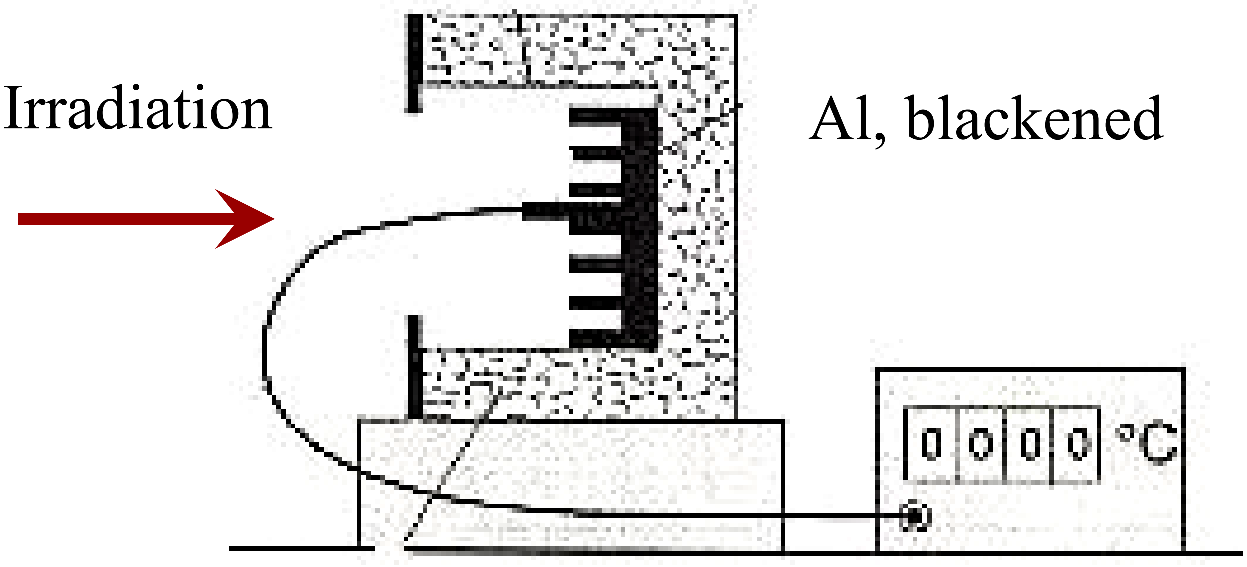
Thermo-Column (Moll)

Thermosäule nach Moll
Thermo-Column
Empfindlichkeit (Sensitivity) 0,16 mV/mW
Wellenlängenbereich (wavelenght) 150 nm – 15000 nm
Innenwiderstand (Internal Resistance) 10 Ohm
Einstelldauer (duration for measurement) 2-3 s
Eintrittsfläche (sensitive area) diameter 34 mm

Thermo-Column
thermo-couples
In series

Measurement of the total irradiance

Irradiation



Al, blackened

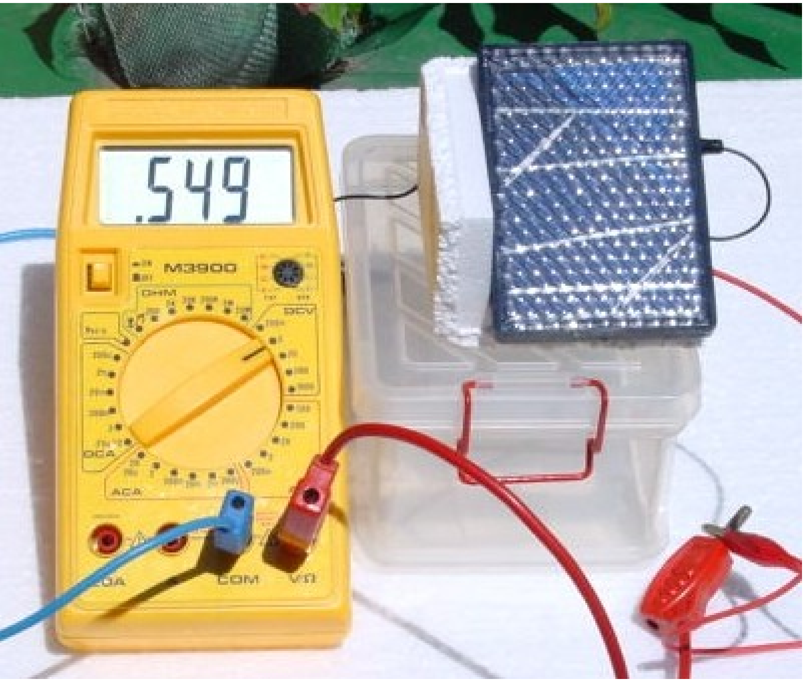
styrofoam

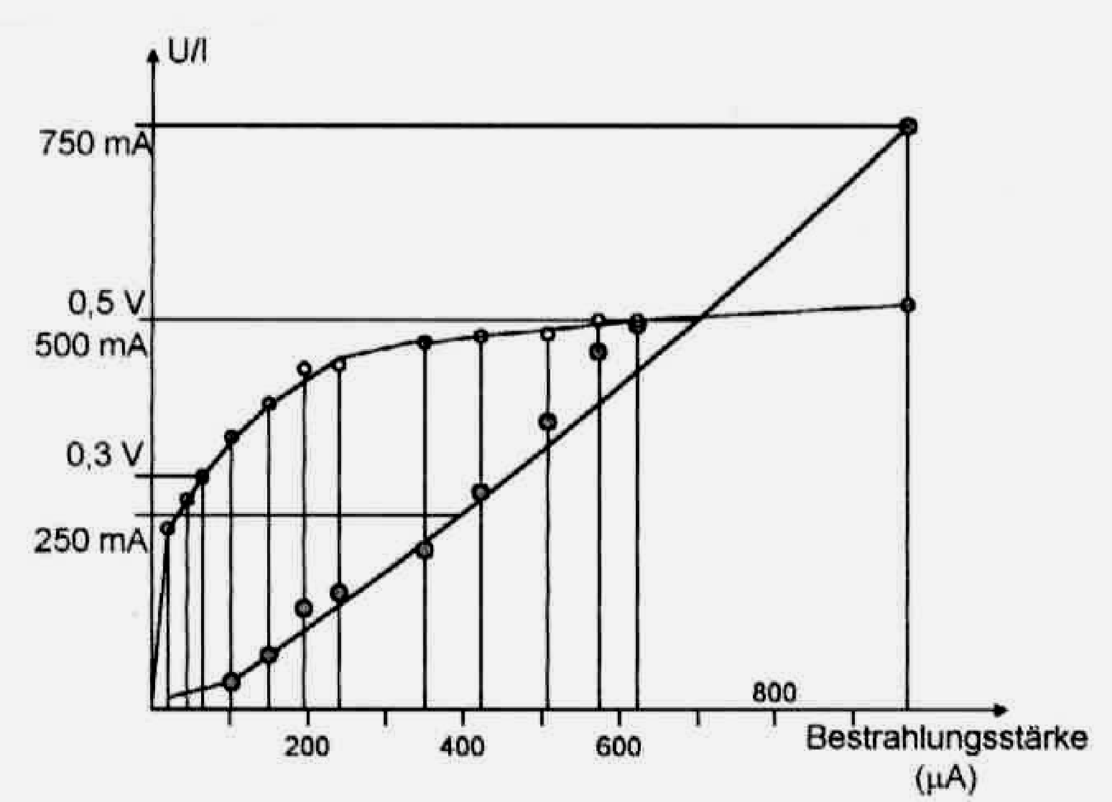
temperature measurement 0,01 K accurateness

$$dQ\ (J) = \varepsilon \cdot c \cdot m \cdot d\delta$$

ε...absorption coefficient ~ 0,95
c...specific warmth, Al- 0,89 kJ/kg.K
m...mass-kg
dδ..temperature difference – K
Measurements duration up to thermal balance

Characteristic Lines of a Solar Cell





Photovoltage

$$U_0 = \frac{kT}{e}\cdot\ln\left(\frac{q}{n_0\cdot\frac{D_E}{L_E}+p_0\cdot\frac{D_L}{L_L}}+1\right)$$

mit:

q..Zahl der je Sekunde pro Flächeneinheit der p-n-Schicht gebildeten Elektron-Loch-Paare

L...Diffusionslänge

D...Diffusionskonstante

n_0, p_0: Gleichgewichtskonzentration der Elektronen bzw. Elektronenlöcher

t...Lebensdauer der Elektron-Loch-Paare

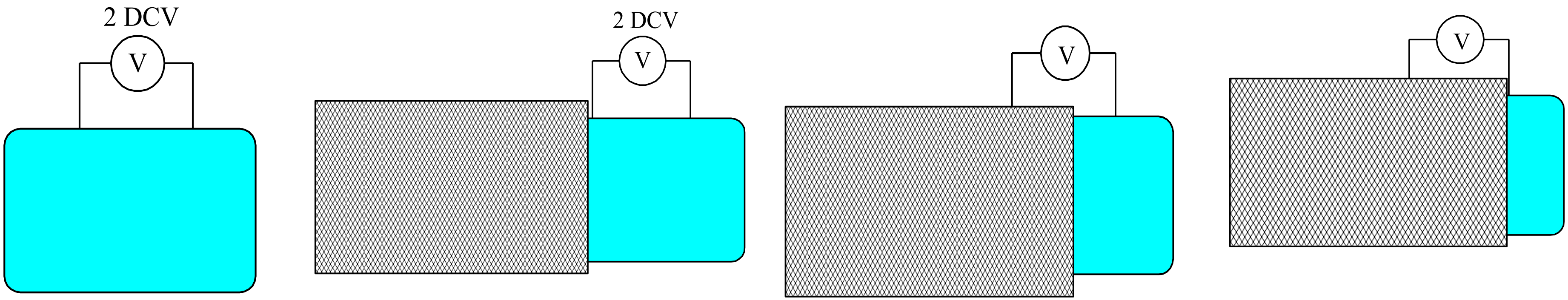
Sonderfall:

$D_E = D_L$, $L_E = L_L$, $n_0 = p_0$:

$$U_0 = \frac{kT}{e}\cdot\ln\left(\frac{j}{I_0}+1\right)$$

mit j = q.e

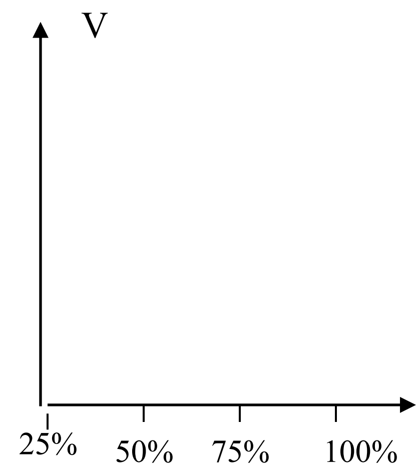
Photovoltage – Exposed Area



The Solar Cell is directly connected to the voltmeter. (2 DCV)

Cover parts of the surface area and observe the voltage in any case !

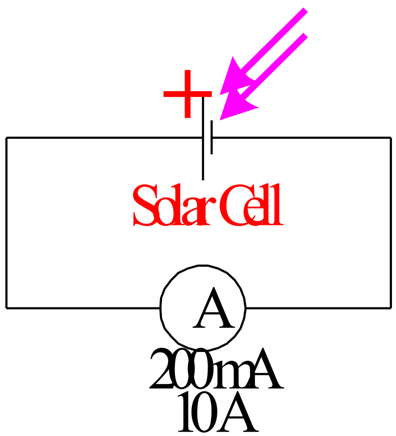
Not covered..........................U=....... V
$\frac{1}{4}$ of the surface covered....U=....... V
$\frac{1}{2}$ of the surface covered...U=....... V
$\frac{3}{4}$ of the surface covered....U=........V

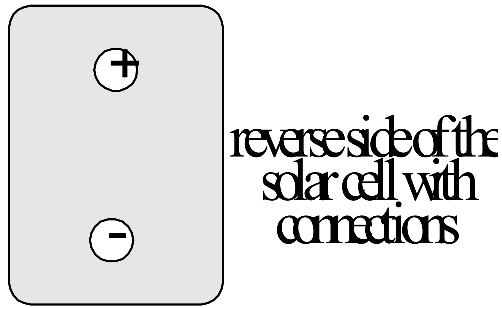


Conclusion:

Short-Circuit-Current of Solar Cells

The Solar Cell is directly connected to the ammeter.





The intensity of the short circuit current is direct proportional to the irradiance.

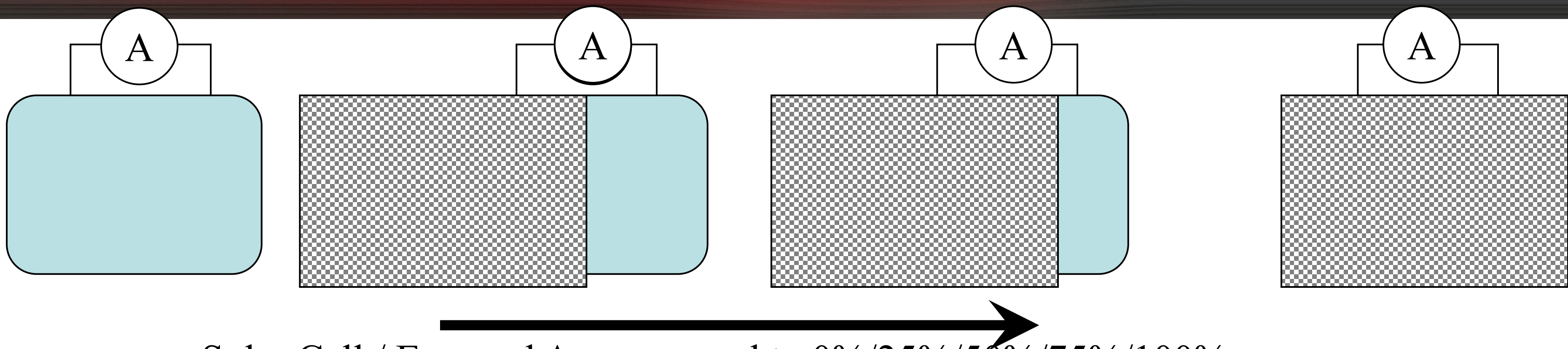
The short circuit current is measured at different irradiances.

	I in mA
dim room	
bright room	
shadow	
sun	

You may draw a diagram now.

By this you can measure the illumination.

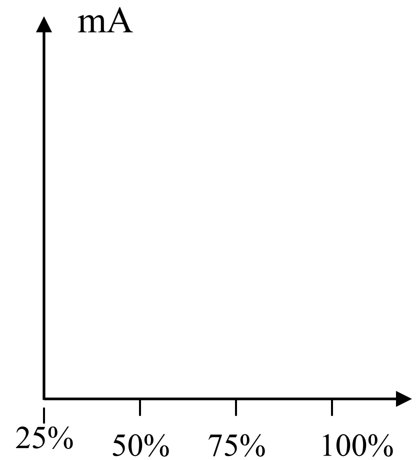
Short-Circuit-Current of Solar Cells



Solar Cell / Exposed Area covered to 0%/25%/50%/75%/100%.

The Solar Cell is directly connected to the ammeter.

Cover parts of the surface area and observe the intensity of current in any case !



Despite the surface is totally covered current is to be measured.
This demonstrates the influence of IR.

Dependencies

The Solar Cell is directly connected to an ammeter.

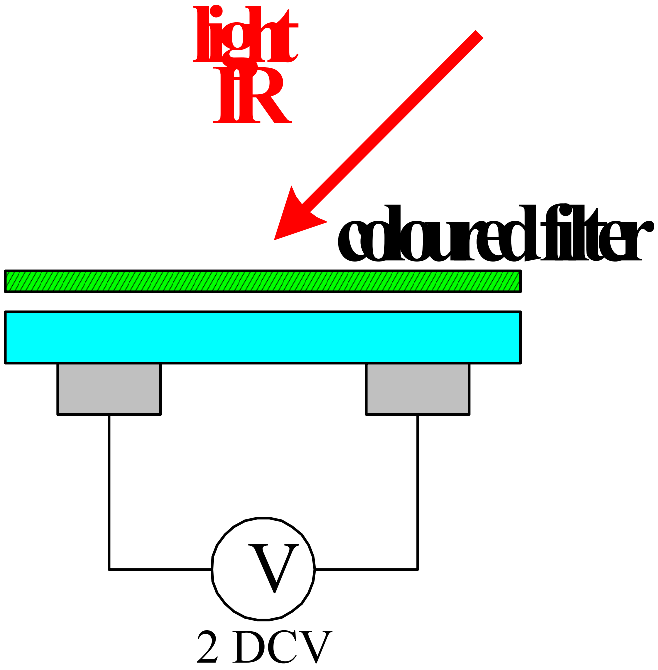
The Solar Cell is directly connected to a voltmeter.

Different Surfaces

about the same voltage – only dependent on
the irradiance

Short current´s intensity depending on the irradiance
and proportional to the surface.

Sensitiveness – Spectral Range

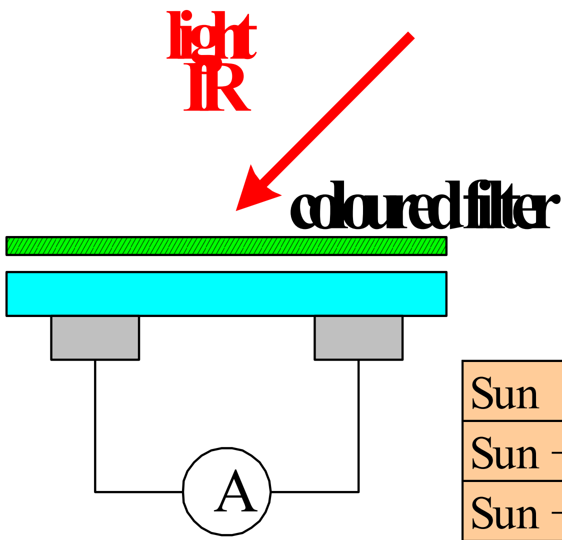


To which colour the solar cell is most sensitive?
Colour means part of the spectral range - visible and infrared.

Sun	U = ... V
Sun + red coloured filter	U = ... V
Sun + green coloured filter	U = ... V
Sun + blue coloured filter	U = ... V
Infrared	U = ... V

Highest sensitiveness to red indicates Silicon.

Sensitiveness – Spectral Range

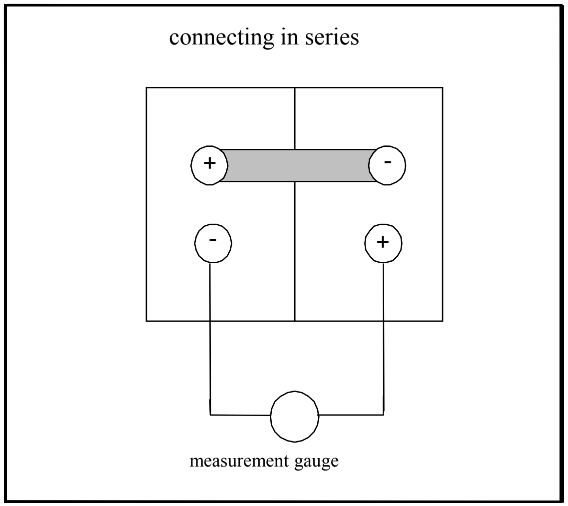


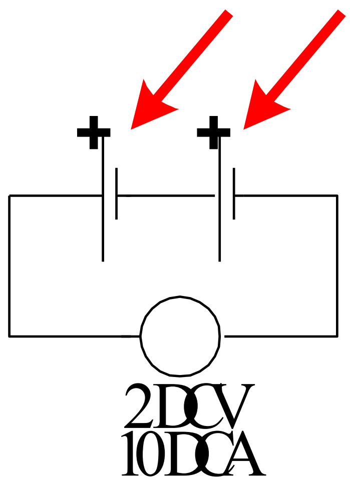
To which colour the solar cell is most sensitive?
Colour means part of the spectral range - visible and infrared.

Sun	I = ... mA
Sun + red coloured filter	I = ... mA
Sun + green coloured filter	I = ... mA
Sun + blue coloured filter	I = ... mA
Infrared	I = ... mA

The Solar Cell shows the highest efficiency in the red part of the spectral range. This is an indicator for Silicon.

Connecting Solar Cells into Series





Measure the open circuit voltage of any of the two solar cells:

U_1 = ... V

U_2= V

Measure the short current intensity of any of the two solar cells:

I_1 = ... mA

I_2= .... mA

Connect the solar cells into series.

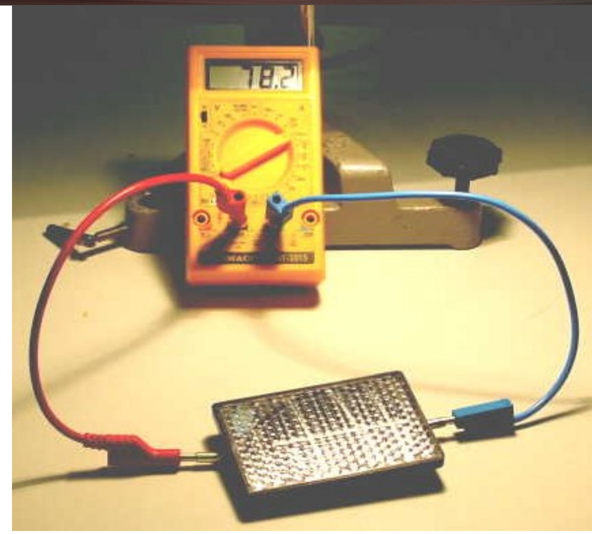
Measure now the open circuit voltage as well as the short current intensity of both solar cells:

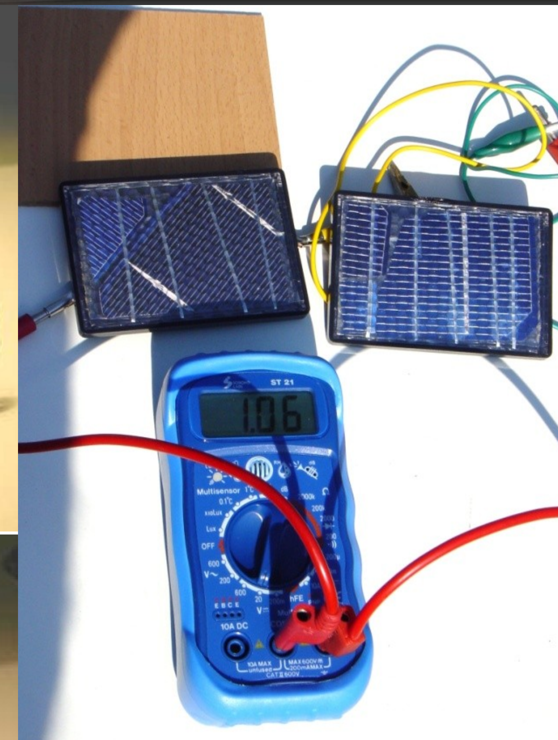
$U_1 + U_2$ = ... V

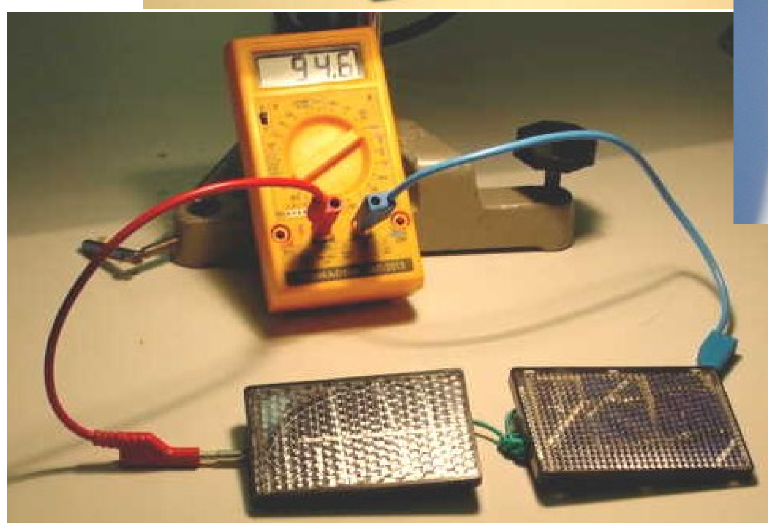
$I_1 + I_2$ = ... mA

Voltages are added, intensities remain the same.

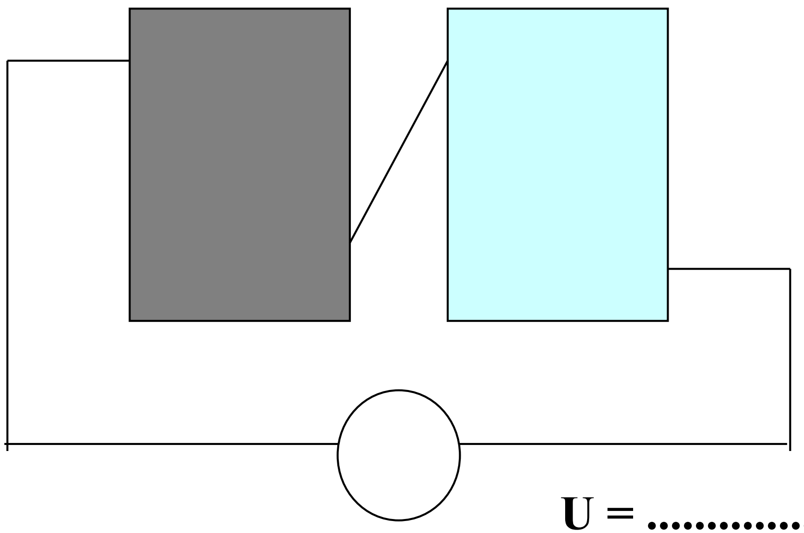
Connecting Solar Cells into Series







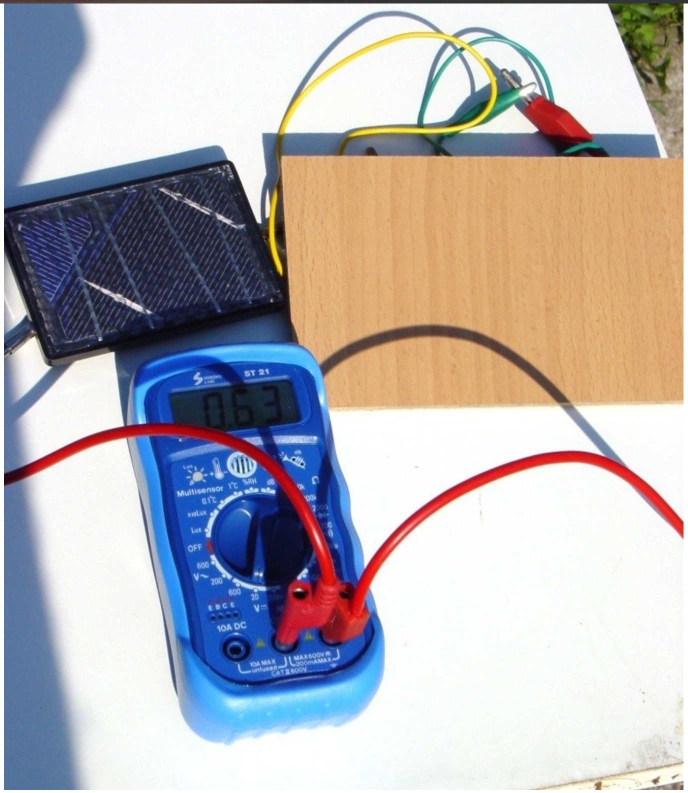
Cover one solar cell. This one cannot produce photovoltage.



mA / V

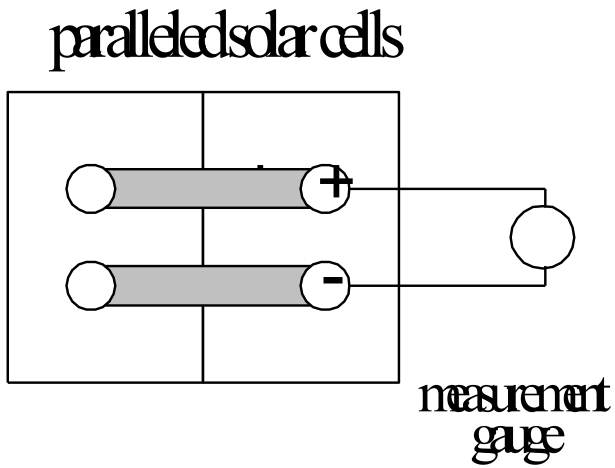
U = ... V

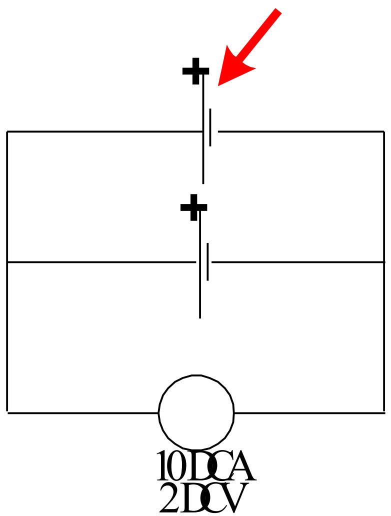
I = ... mA



The internal resistance of the clouded solar cell is rather high,so the current´s intensity goes tozero. The clouded solar cell blocks the current and therefore has to be bridged by an open-circuit-diode.

Connecting Solar Cells into Parallel





Measure the open circuit voltage of any of the two solar cells:

U_1 = ... V

U_2 = ... V

Measure the short current intensity of any of the two solar cells:

I_1 = ... mA

I_2 = ... mA

Connect the solar cells into parallel.

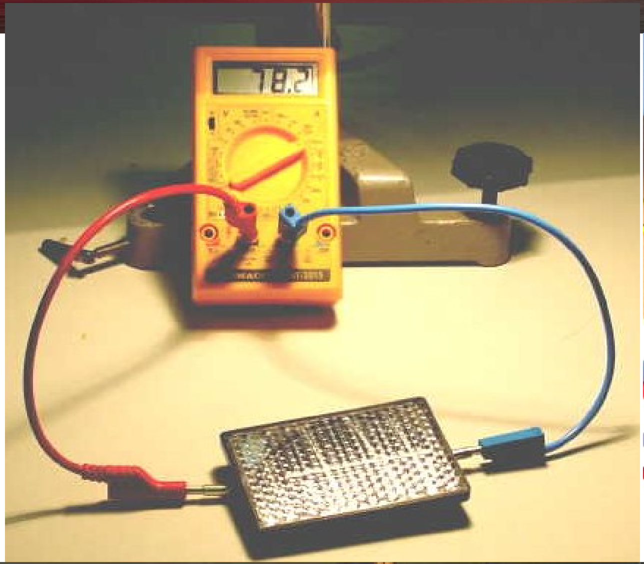
Measure now the open circuit voltage as well as the short current intensity of both solar cells:

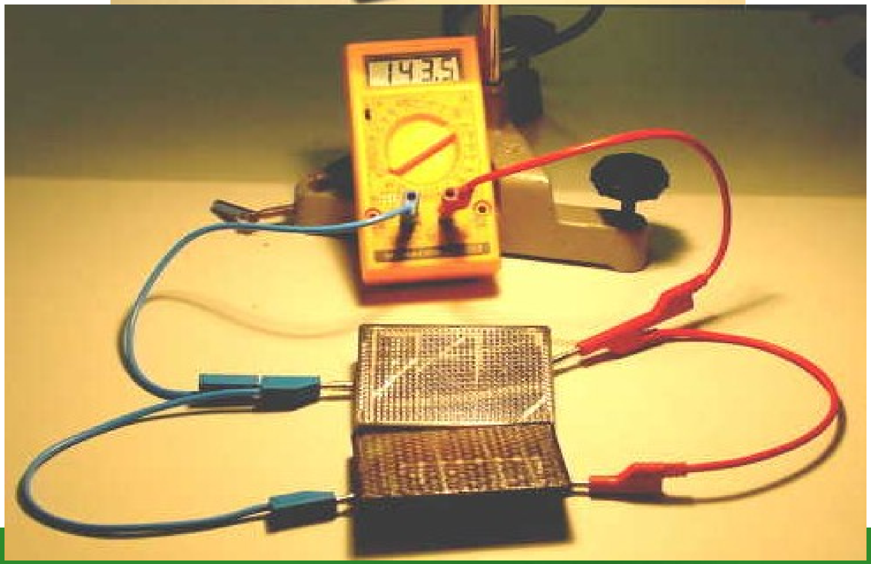
$U_1 + U_2$ = ... V

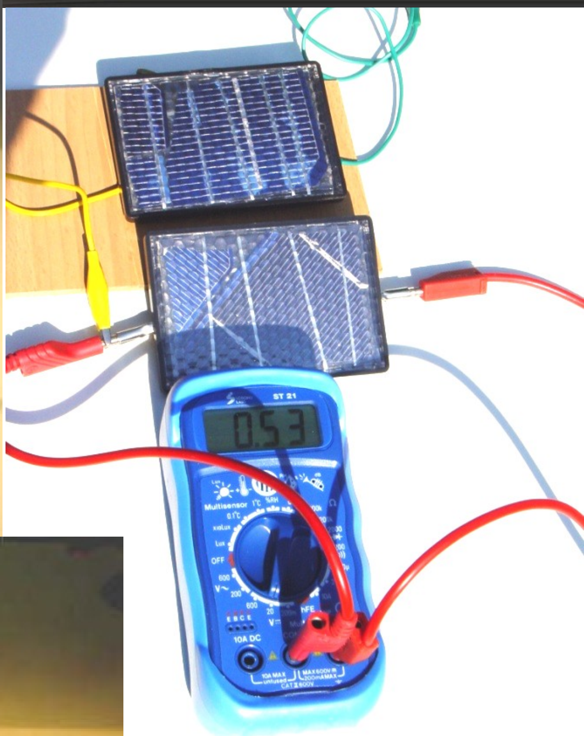
$I_1 + I_2$ = ... mA

Intensities are added, voltages remain the same.

Connecting Solar Cells into Parallel

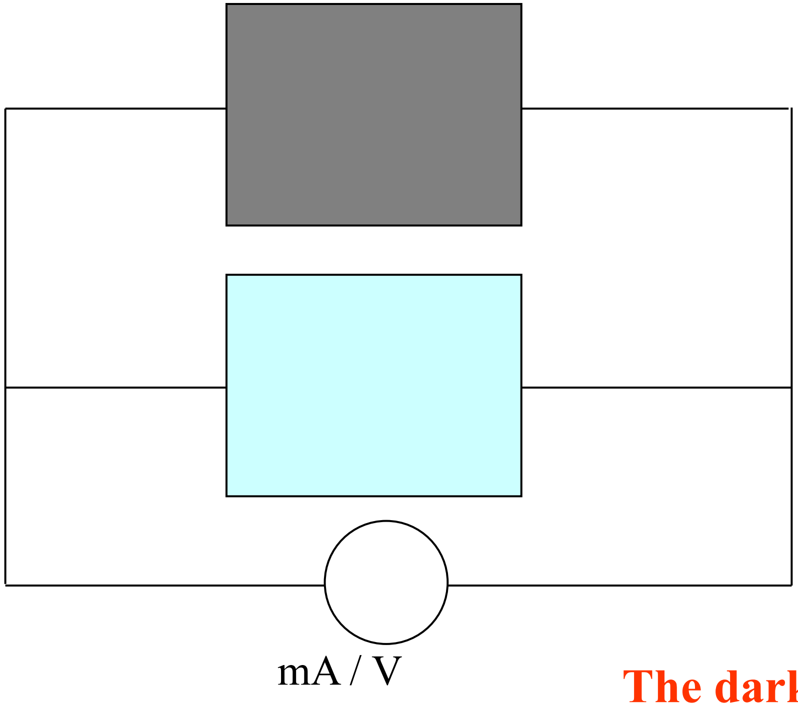


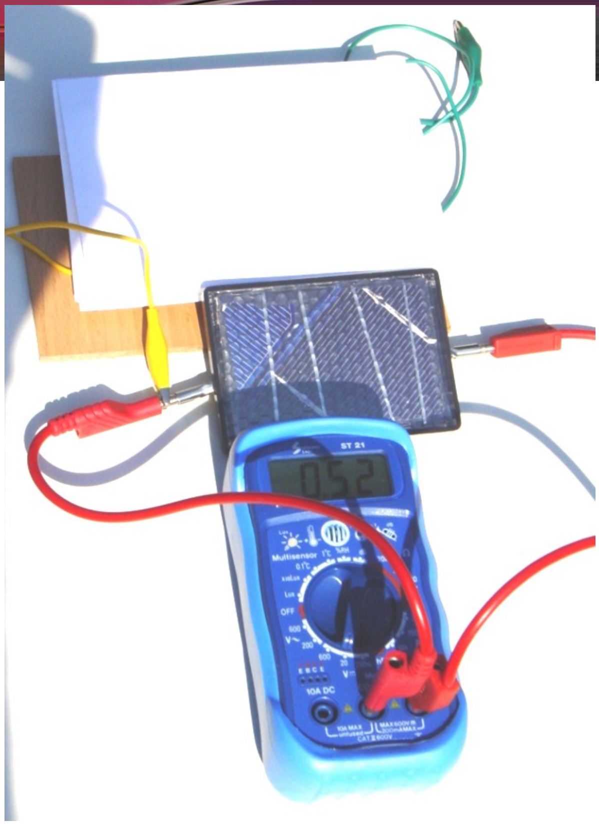




Connecting Solar Cells into Parallel

Cover one solar cell. This one cannot produce photovoltage.



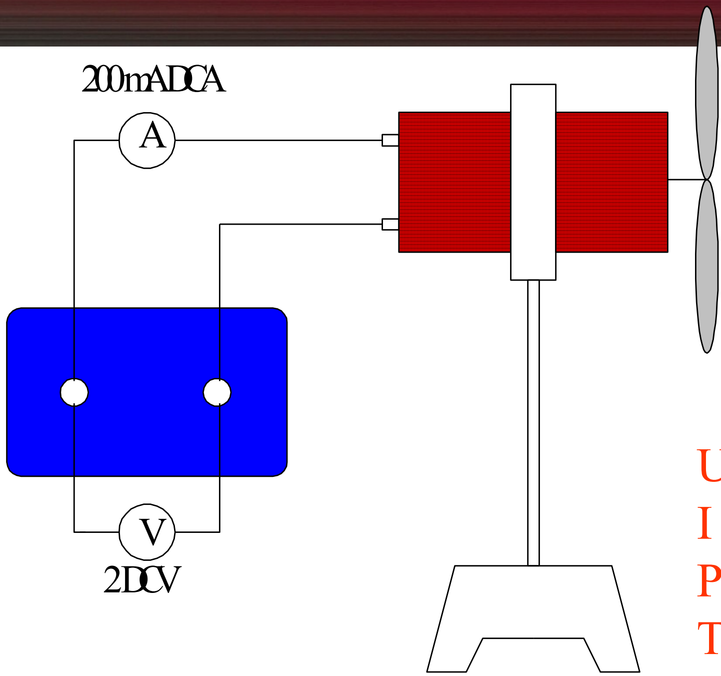


U = ... V

I = ... mA

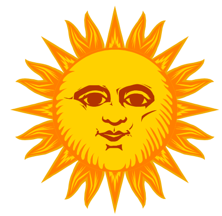
The darkened solar cell is out of order, this deminishes the current. It has the effect of reducing the exposed surface area.

Running an Engine

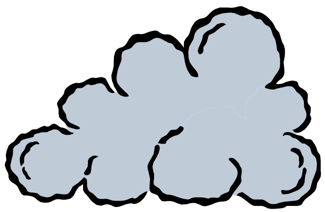


Run the engine at different illumination - sunlight, shadow, indoor.

For shadowing you may use a grid.



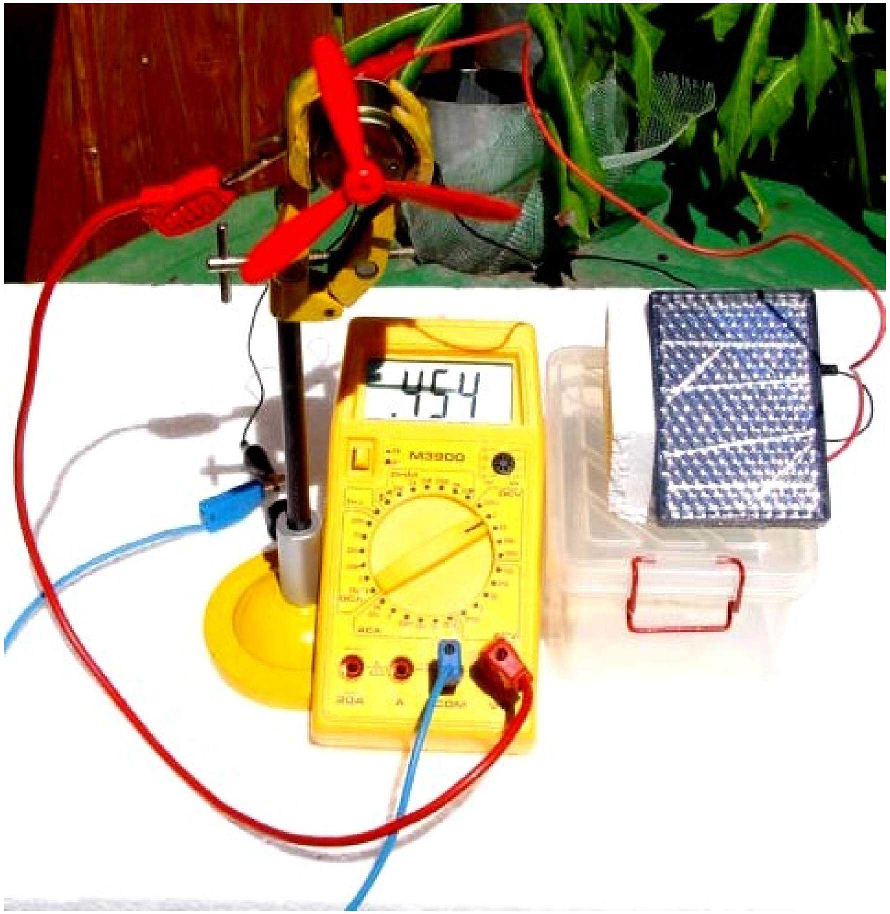
U = ... V
I = ... mA
P = ... mW
The engine runs...
...fast
...slow
...not

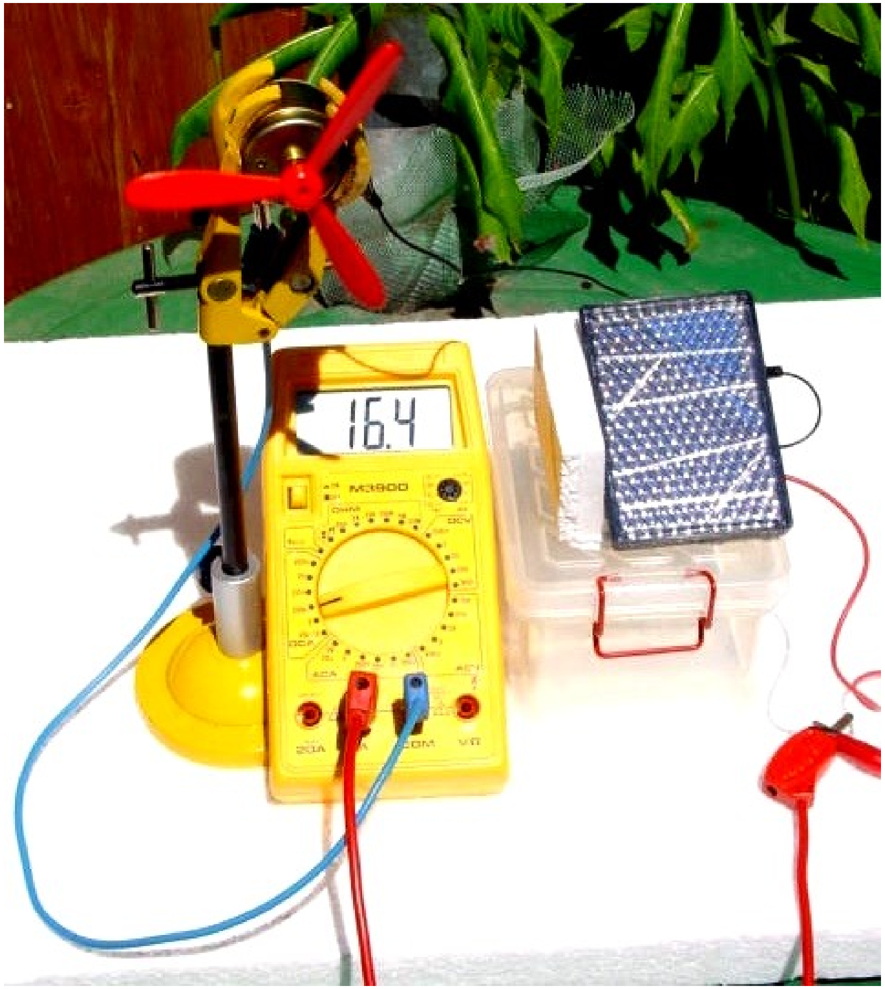


U = ... V
I = ... mA
P = ... mW
The engine runs...
...fast
...slow
...not

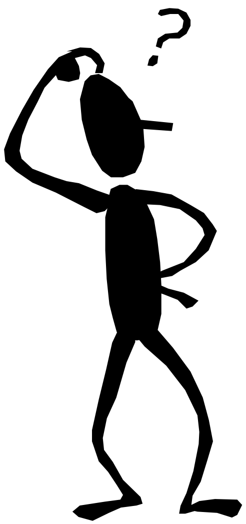
U = ... V
I = ... mA
P = ... mW
The engine runs...
...fast
...slow
...not

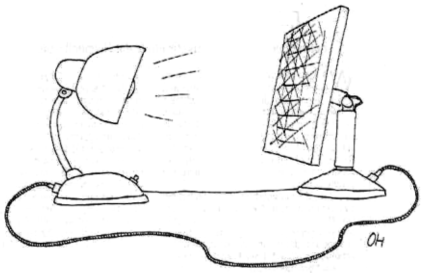
Running an Engine





Efficiency





$\eta = F \cdot A \cdot Q$

fill factor...share of energy being transfered from the solar cell to the appliance.

absorption ability, depends on material and frequency of radiation

yield of quanta energy, abundance, to which photons solve electrons.

For Si it is: $\eta = 0{,}8 \cdot 0{,}7 \cdot 0{,}21 = 0{,}12$ (12%)

Efficiency

matter		efficiency theor.	efficiency pract.
Si	monocryst.	15%	11-16%
	polycryst.	10-15%	9-12%
	amorphous	20%	11% (4-7%)
GaAs, CdTe, GeS, CdS, ZnSe		up to 20%	up to 16%
	technics		16%
	high-efficiency cells		24%
	Tandem-, sandwich		up to 32%

Calculating the Efficiency / Engine´s Experiment

- Measurement of the irradiance by means of a calibrated solar cell:
- x W/m²
- Dimensions of the solar cell (battery) used:
- l = ... cm, b = ... cm
- A = ... m²
- Irradiance P:

P = x . A = ... W

$$\eta \quad \frac{W}{V}$$

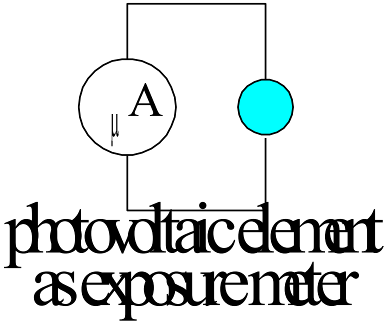
- Measurement of the engine´s power:
- U = ... V
- I = ... mA = ... A
- P = U . I = ... W_1

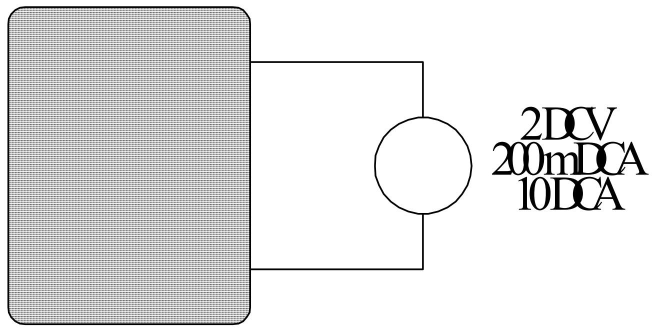
Calculation with EXCEL

Open the table on your disc and calculate !

Solar Cell	Fill in	Result	Comment
Irradiance in W/m²		0	
Length of the solar cell in cm			
Width of the solar cell in cm		0	A in m²
Power irradiated to the solar cell		0	P in W
Engine			
Intensity of Current in mA		0	I in A
Voltage in V		0	U in V
Power of the engine in Watt		0	P_1 in W
Efficiency		k.A	

The Characteristic Line

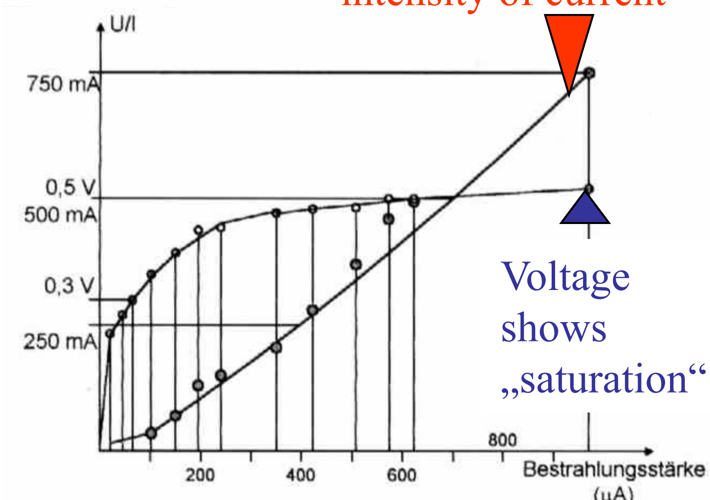




Measured values...

Beleuchtungs-stärke in µA	Leerlauf-spannung in V	Kurzschluss-stromstärke in mA
2,6	0,055	0,27
7	0,08	0,5
20	0,23	6,8
23	0,24	7,6
29	0,257	8,6
35	0,26	10
45	0,277	12,15
64	0,31	17,3
102	0,346	36
150	0,39	64
194	0,444	128
240	0,48	145
350	0,472	193
422	0,476	280
508	0,491	370
572	0,506	460
621	0,502	496
970	0,528	750

Linear increasing intensity of current



Voltage shows „saturation“

Calculate the resistance when being dark:

$I_K = 2{,}6\ \mu A$

$U = 0{,}055\ V\ /\ I = 0{,}17\ mA$

$R = 204\ Ohm$

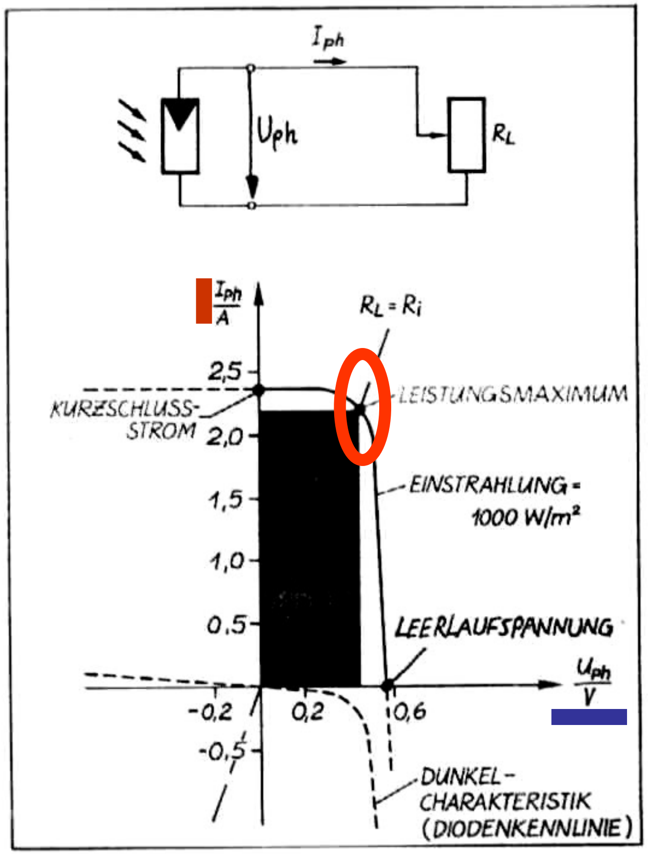
...when being bright:

$I_K = 610\ \mu A$

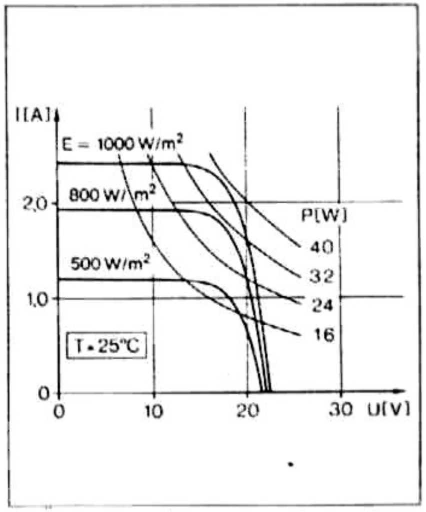
$U = 0{,}502\ V\ /\ I = 496\ mA$

$R = 1\ Ohm$

The Power Characteristic



Strom-Spannungs-Kennlinie einer 10 cm x 10 cm-Solarzelle bei einer Einstrahlungsstärke von 1000 W/m², ϑ = 25 °C



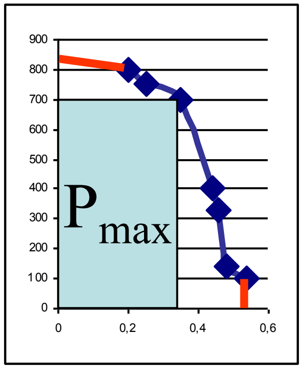
Typische Kennlinien eines Photovoltaikmoduls (AEG)

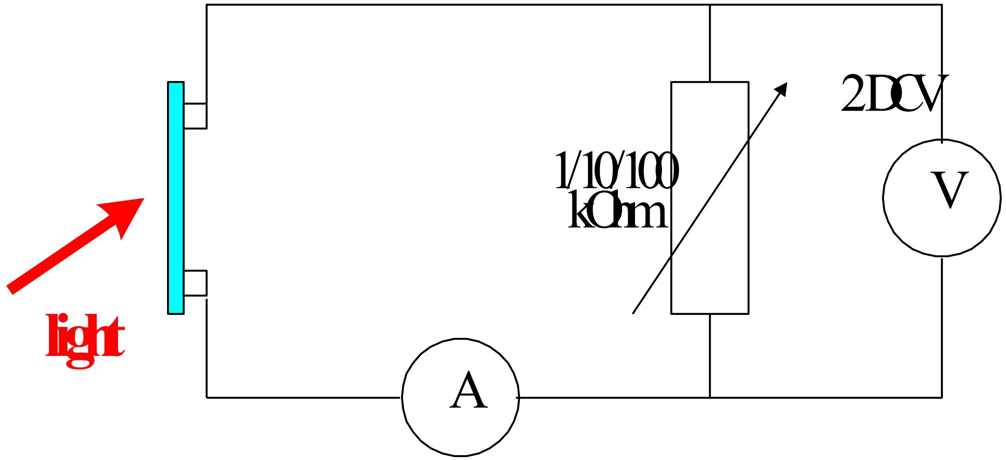
The I-U-characteristic of a Solar Cell
A = 10 cm x 10 cm
irradiance 1000 W/m², δ =25 °C

I...Short Current
U...Open-Circuit-Voltage
Indicated...Power Maximum

Max. power,
if external resistance equals
the internal resistance
of the solar cell.

The Power Characteristic





Problem was:
adaption of the values
of the external resistor

Voltage in V	Current in mA	Power in mW
0	860	0
0,54	100	54
0,48	140	67,2
0,46	330	151,8
0,44	400	176
0,35	700	245
0,25	750	187,5
0,2	800	160
0,55	0	0

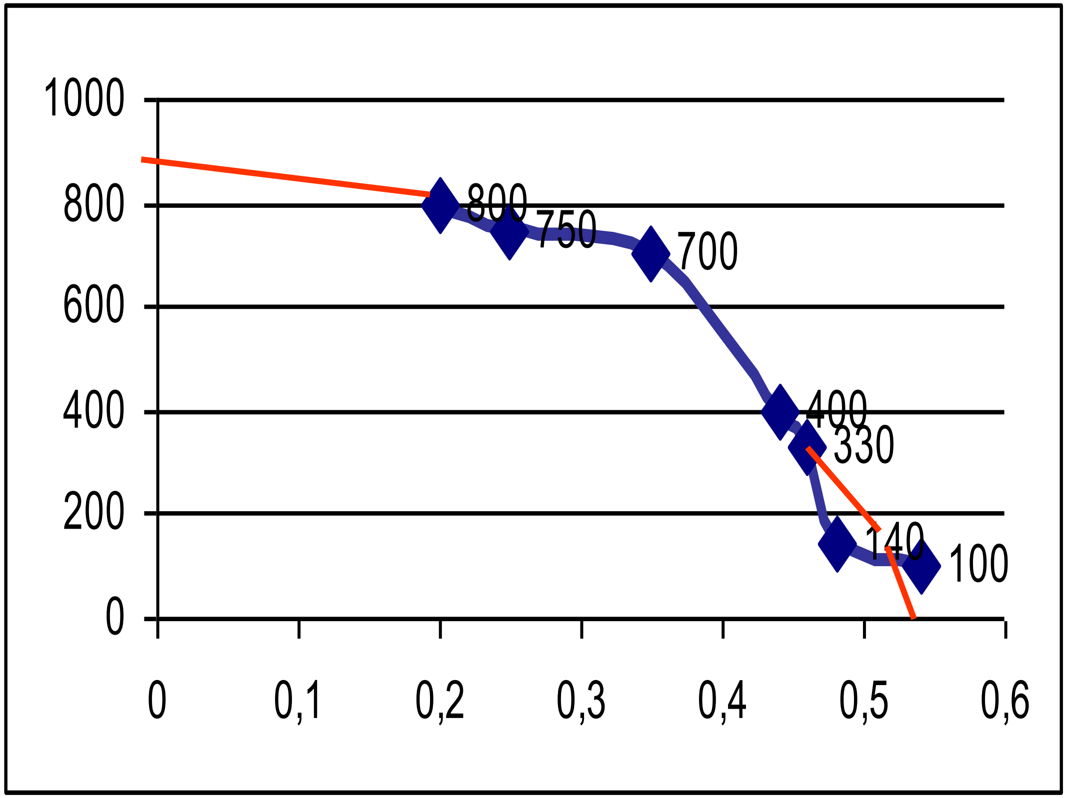
Max. power at U = 0,35 V and I = 700 mA

P_{max} = 245 mW

The Power Characteristic

Problem was:
adaption of the values of the external resistor

Caused by this:
problematic characteristic power line



The Dependence on Temperature

Expose the solar cell to an IR-radiator as it is a bulb with power P = 120 W or the sun.

Do not overheat the solar cell, it could be destroyed.

Duration of Time in min	Voltage in V	Duration ofTime in min	Voltage in V
0	0,561	8	0,493
1	0,550	9	0,488
2	0,540	10	0,482
3	0,530	11	0,477
4	0,520	12	0,468
5	0,514	13	0,464
6	0,507	14	0,460
7	0,500		

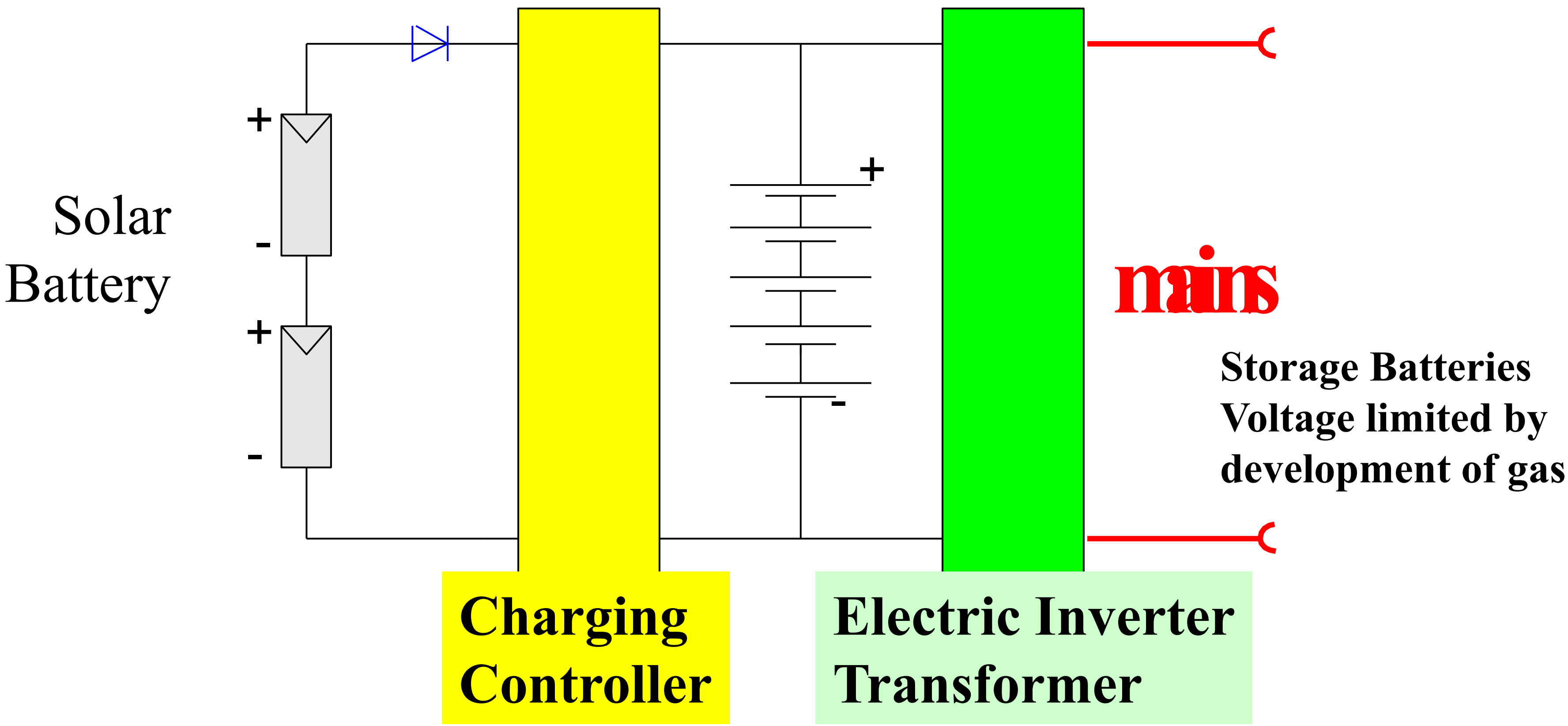
We have measured:

Result: The voltage decreases with increasing temperature.

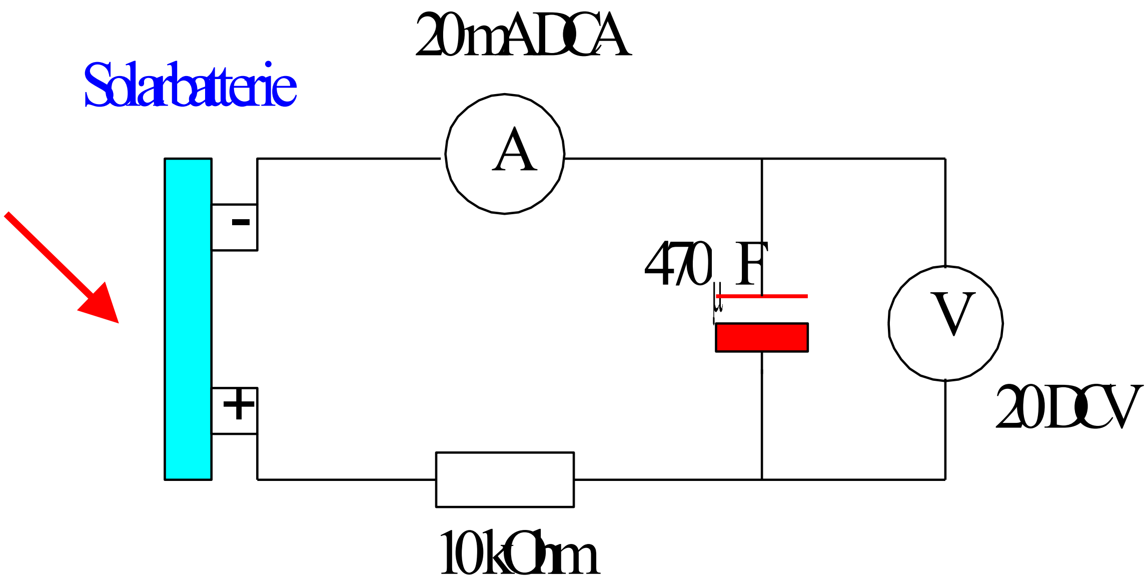
Duration of Time in min	0	1	2	3	4
Intensity of Current in A	0,75	0,77	0,78	0,78	0,78

Result: The intensity of current increases with increasing temperature.

Reverse Blocking Diode



Use a solar battery (voltage about 4 DCV) !!



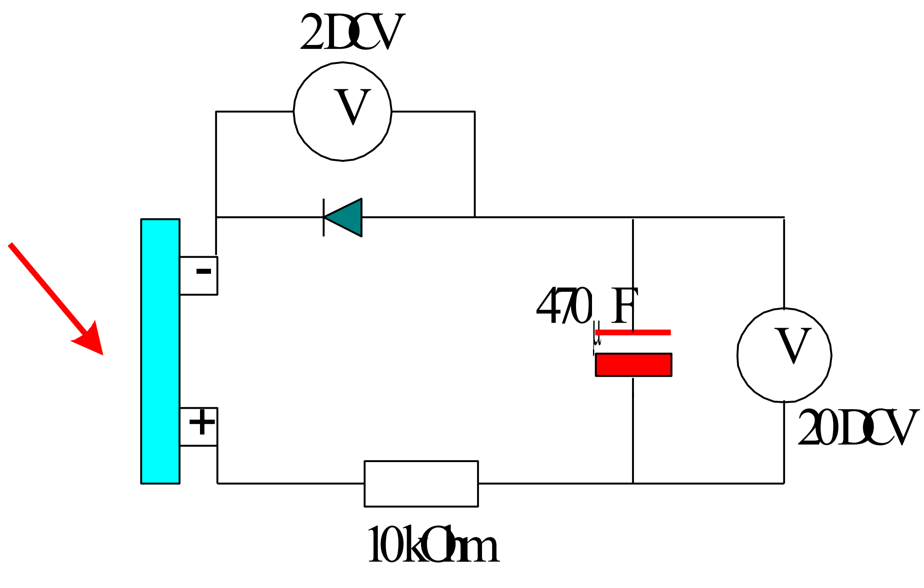
Expose the solar battery to the sun.
The capacitor rapidly is charged up to 4 DCV.
I = ... mA,
U = ... DCV

Cover the solar battery, so it´s surface is dark.
The capacitor discharges cross the solar cell.
I = ...mA,
U = ...DCV

The capacitor is able to store energy, but to avoid discharging in case the solar cell is shadowed, a reverse blocking diode is to be used.

Charging of a Capacitor - Discharging

Use a solar battery (voltage about 4 DCV) !!

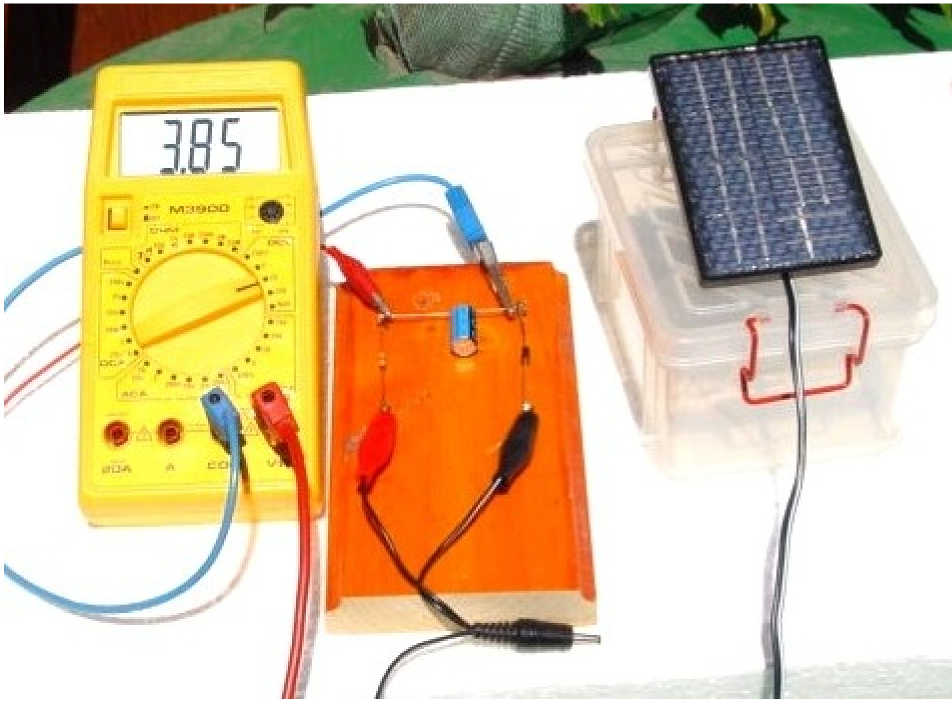


Expose the solar battery to the sun.
The diode is forward biased, so the current can flow.The capacitor rapidly is charged up to
I = ... mA, U = ... DCV
The diode needs about 0,5 V drop in voltage.

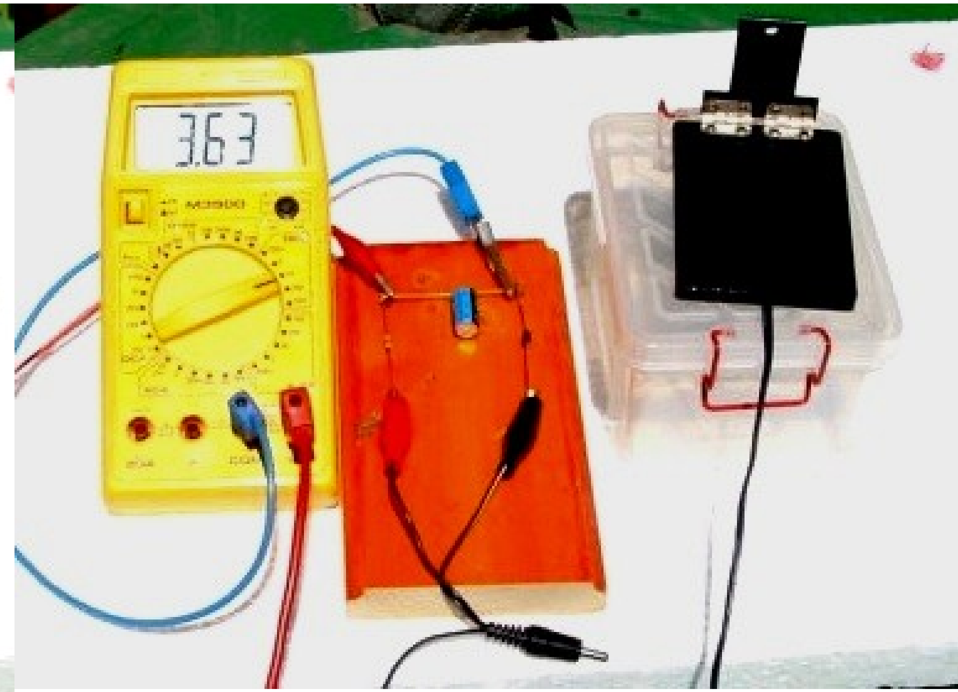
Cover the solar battery, so it´s surface is dark.
The capacitor does not discharge cross the solar cell,
because now the diode is reverse biased.
I = ...mA, U = ...DCV

The capacitor is able to store energy, the reverse blocking diode is a hindrance for discharging.

Charging of a Capacitor - Discharging

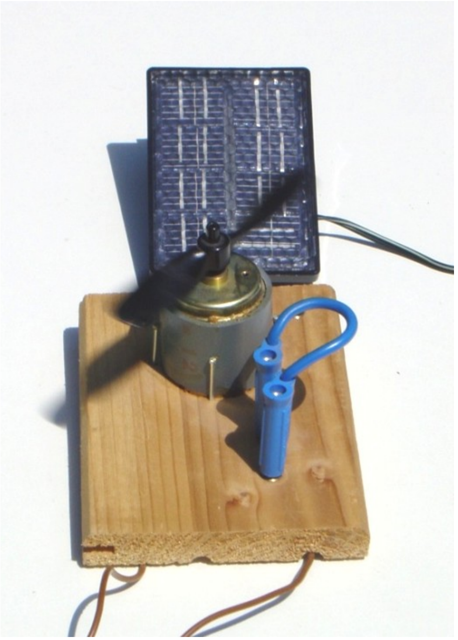


sunshine



darkness

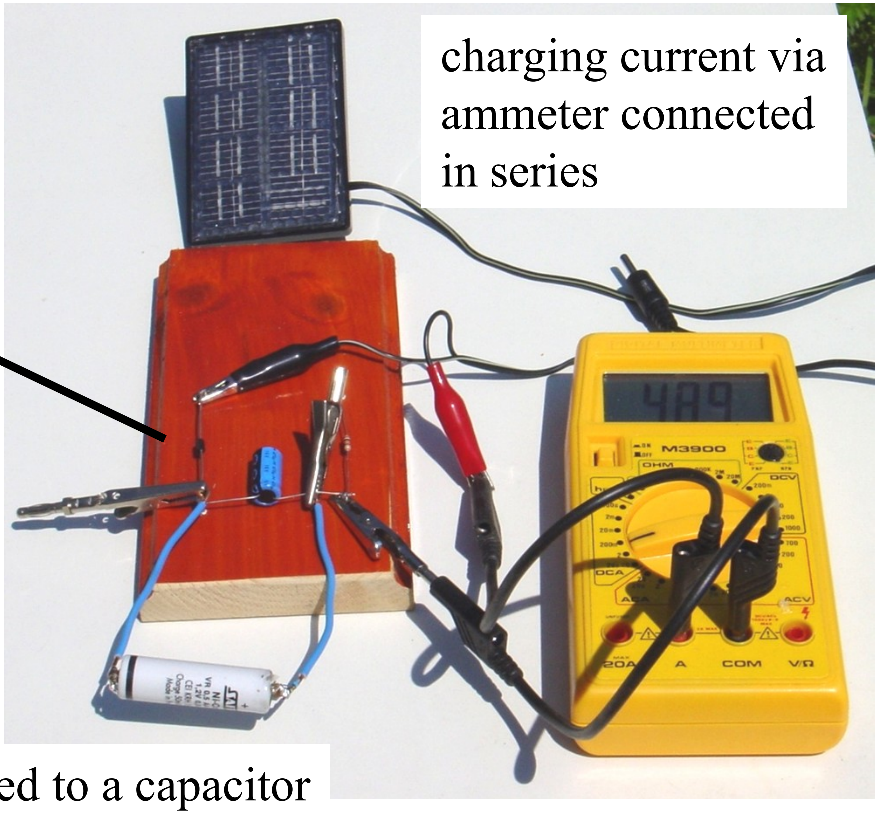
Charging a rechargeable Battery



The solar motor is run by a solar cell exposed to bright sunshine.

The battery is charged by a solar cell.

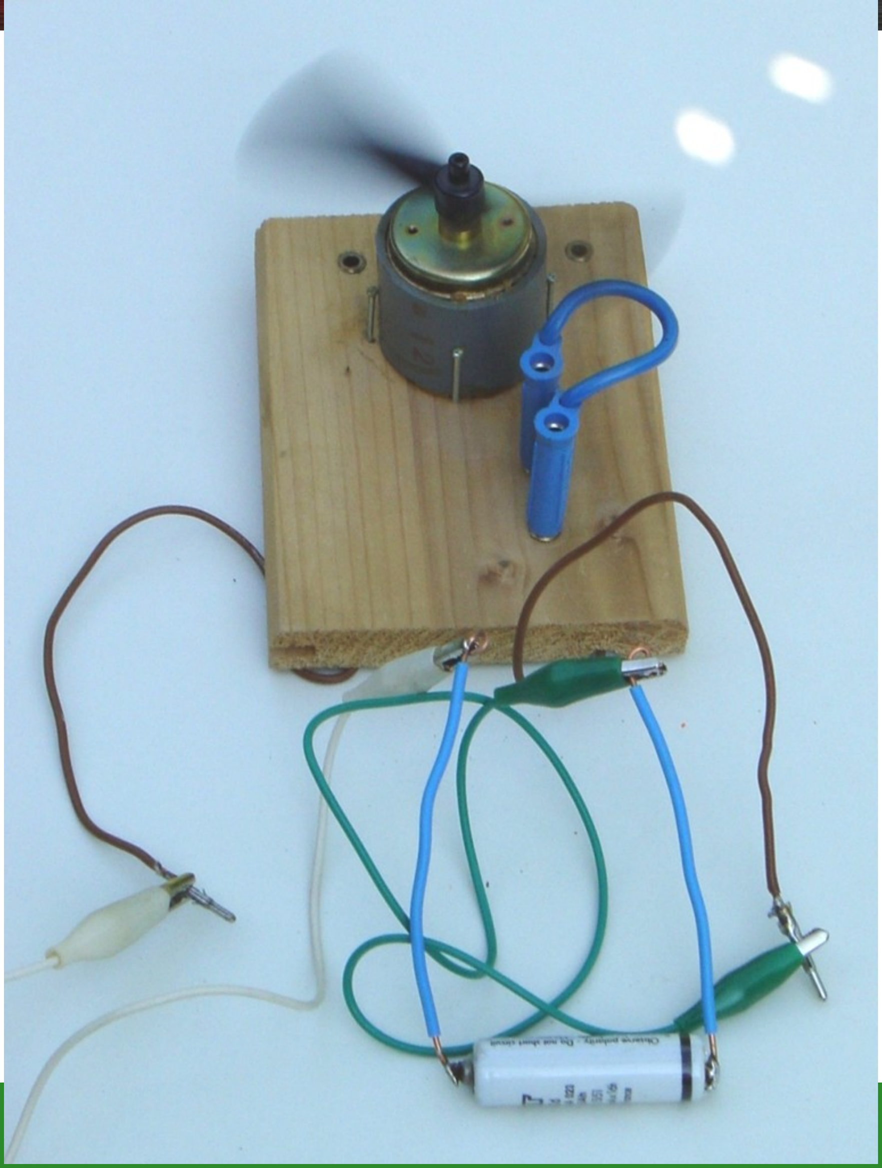
reverse blocking diode



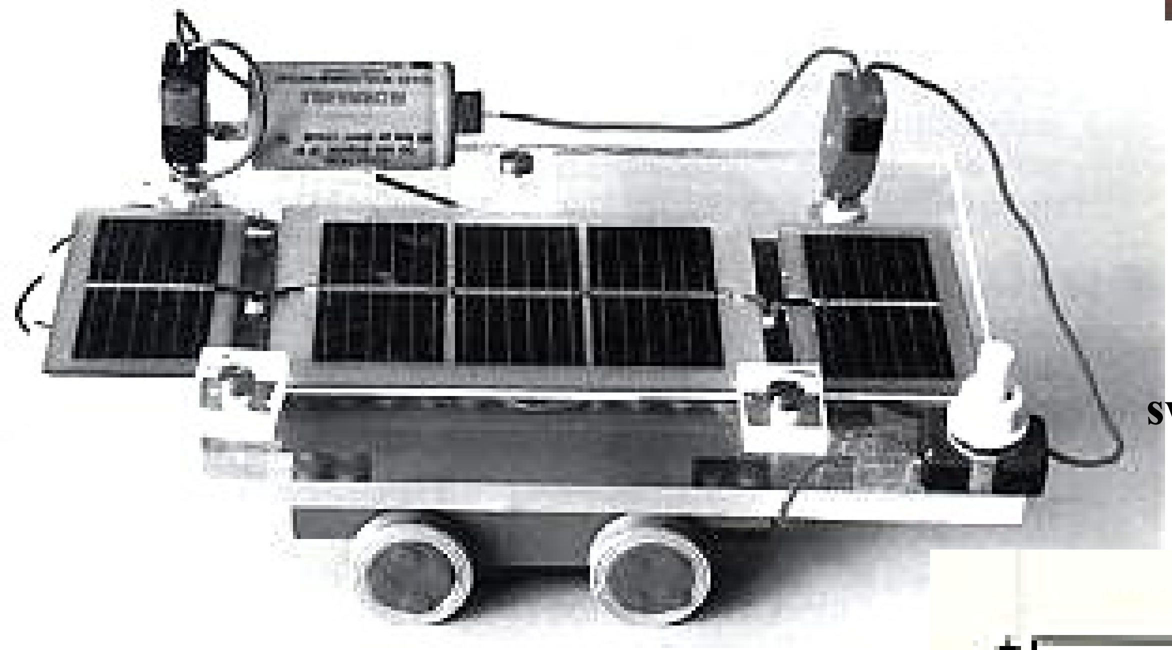
battery paralleled to a capacitor

Charging a rechargeable Battery

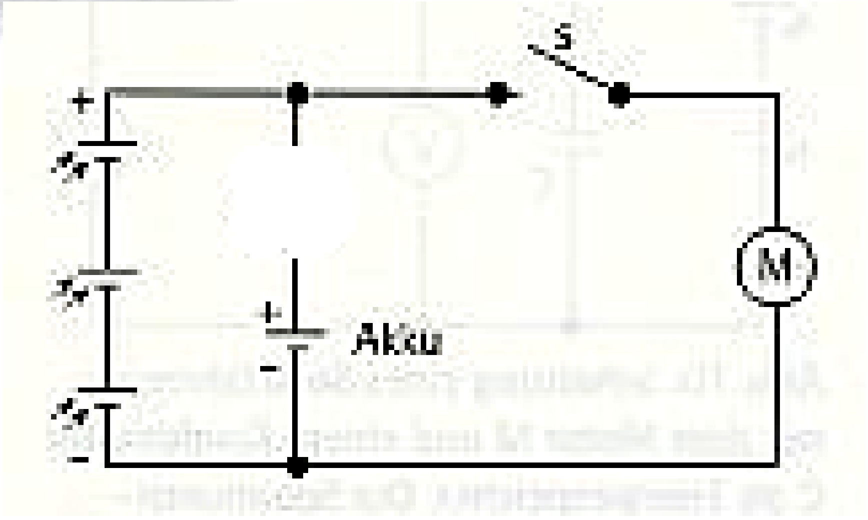
solar engine
run by the
charged battery



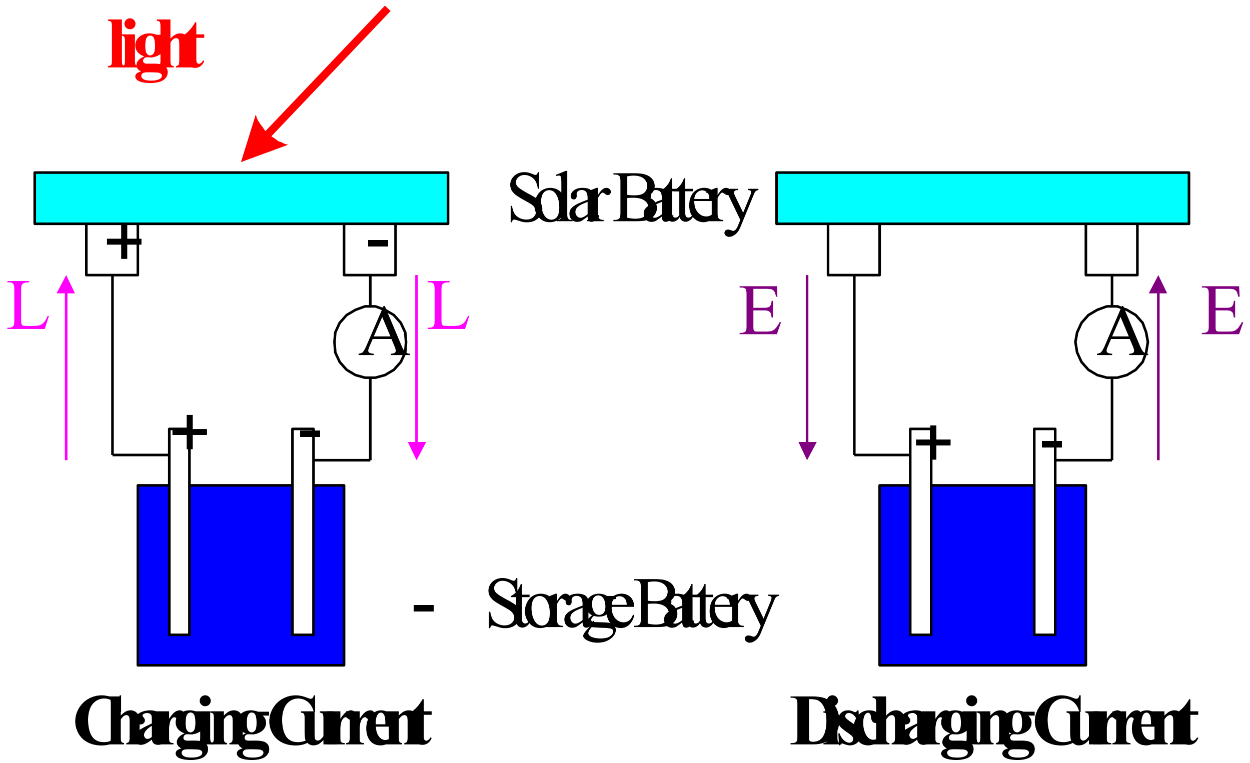
Running a Model



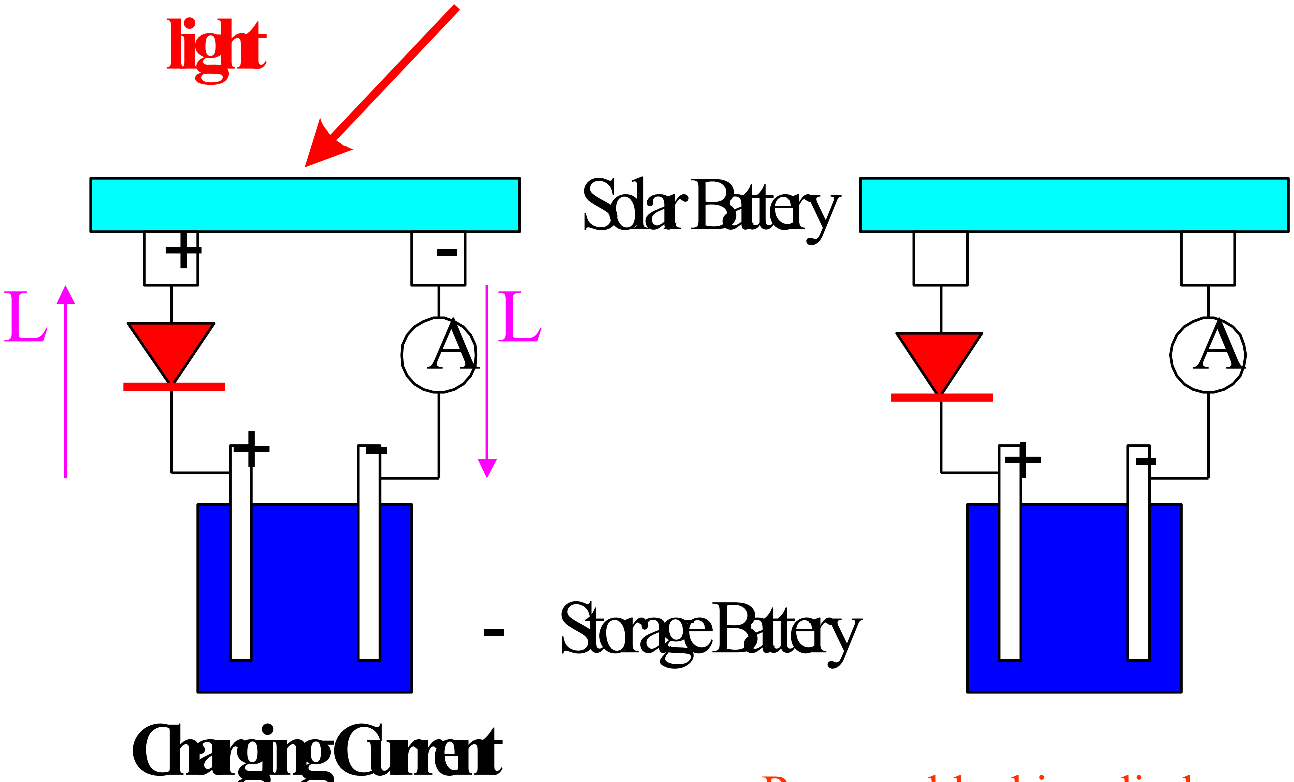
switch to the motor



Storing Energy by an Accumulator

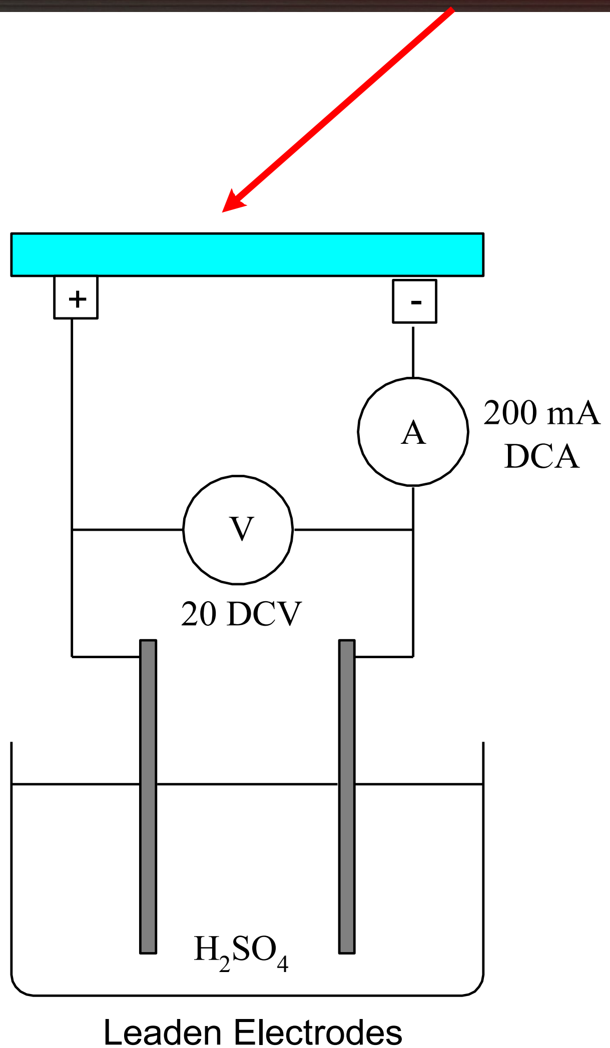


For blocking the dischargement a reverse biased diode is used.



Reverse blocking diode
discharging impossible

Charging an Accumulator



1. Expose the solar battery to the sun.
2. Read U and I every minute and write it into the schedule.
3. After 10 minutes exchange the solar battery by the electric motor.
4. Read U and I every minute. How long it lasts, that the engine runs ?

See table next page

Calculation with EXCEL

Charging			Discharging via Engine		
T in min	U in V	I in mA	T in min	U in V	I in mA

Calculation of the Efficiency

Measurement of the Irradiance: x W/m² (calibrated solar cell); x = ... W/m²
Length of the solar battery: l = ...
Width of the solar battery: b = ...
Surface area A = ... m²
Power irradiated to the surface of the solar battery:
P = A.x W; P = ... W
Time of exposition: t = ... h
Energy absorbed: E = P.t; E = ... Wh

The solar battery runs the electric motor:
Voltage at the end of charging: U_1 = ... V
Intensity of Current: I = ... A
Time of running: t_1 = ... h
Voltage at the end of running the motor:
U_2 = ... V
Power $P_1 = (U_1 - U_2).I$ = ... W
Energy needed for running the motor: $E_1 = P_1 . t_1$=.............Wh

η

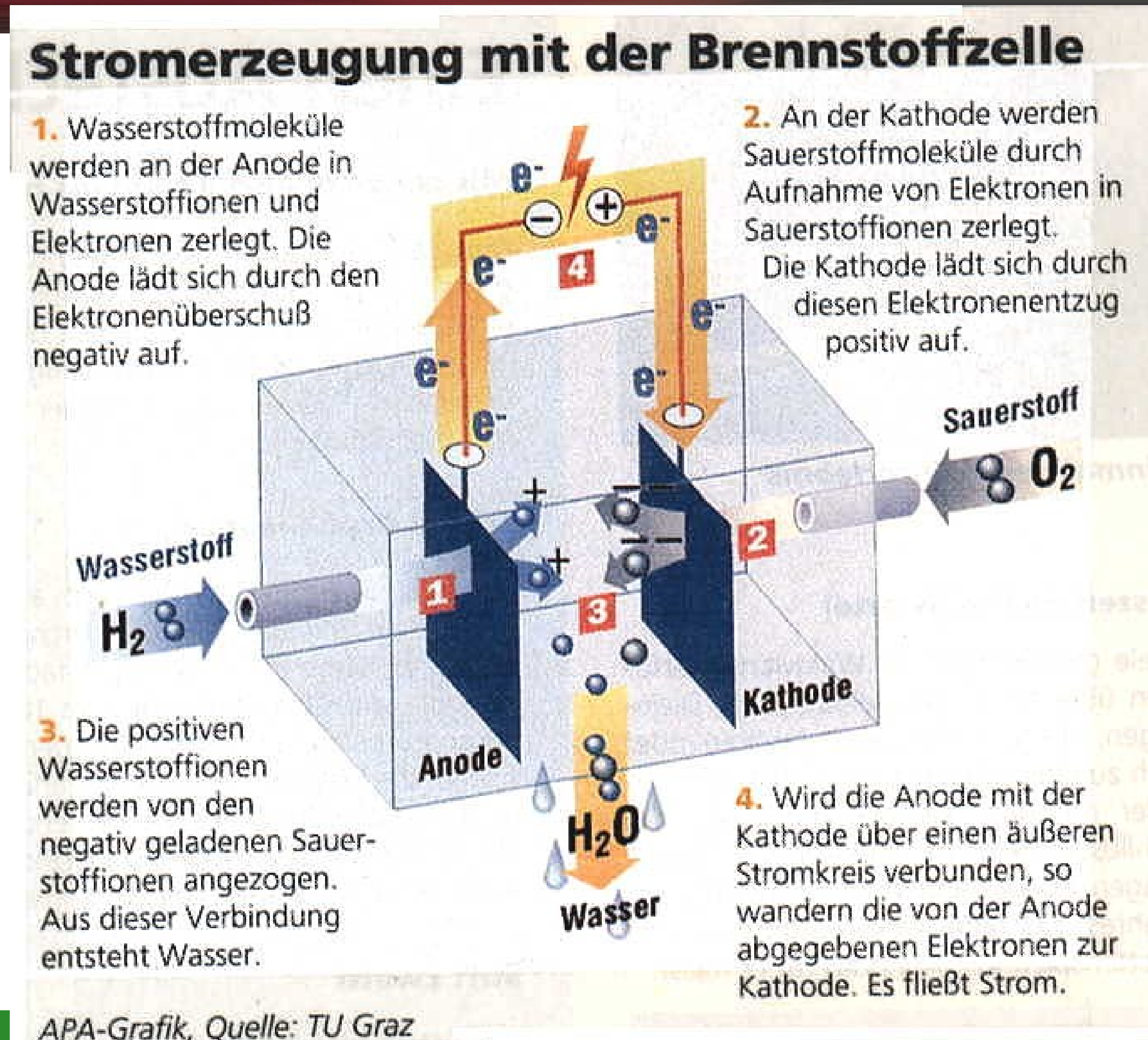
Calculation with EXCEL

Solar Cell	Fill in	Result	Comment
Irradiance in W/m²		0	
Length of the solar cell in cm			
Width of the solar cell in cm		0	A in m²
Power irradiated to the solar cell		0	P in W
Time of exposition in min		0	t in h
Engine			
Starting voltage in V		0	U in V
Intensity of Current in mA		0	I in A
End voltage in V		0	U in V
Power of the engine in Watt		0	P_1 in W
Time of running the motor in min		0	t in h
Efficiency		k.A	

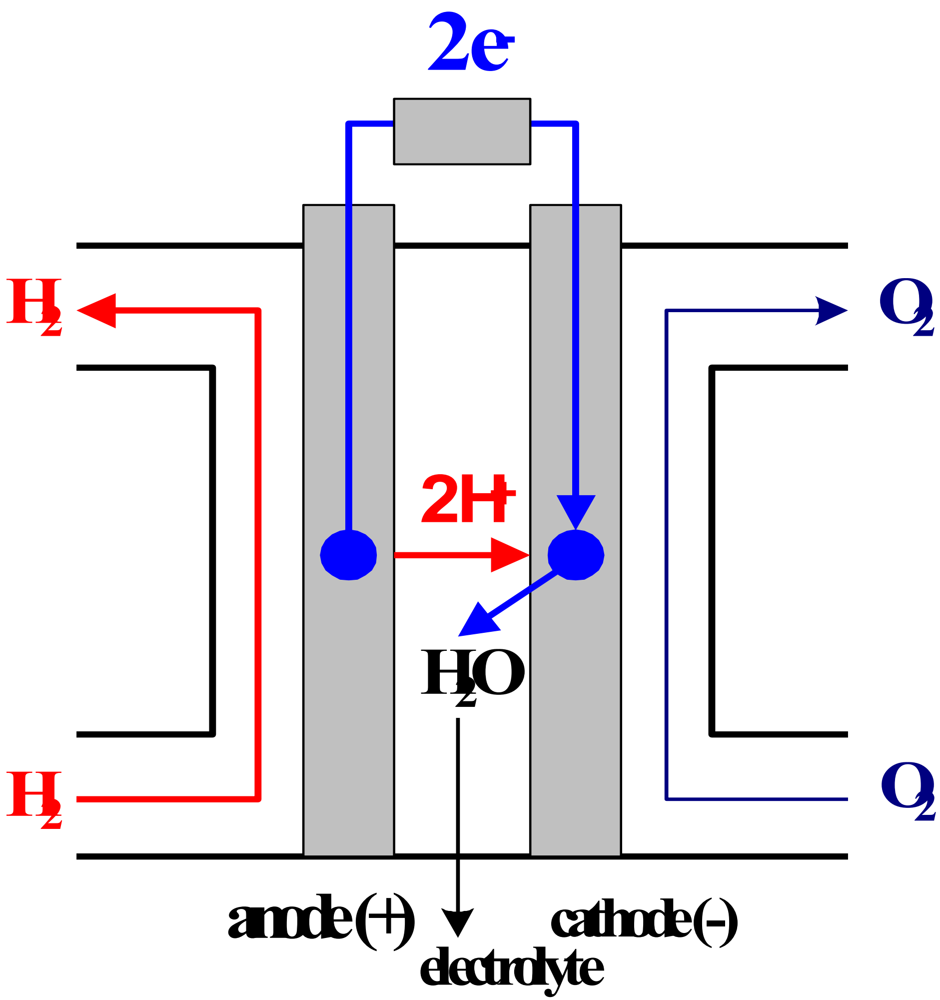
Beause of long time measurement: result are average values

Fuel Cell in Short

Original and Source: Technical University Graz Austria



Fuel Cell in Very Short



Anode´s reaction:

$H_2 \rightarrow 2H^+ + 2\,e^-$

Cathode´s reaction:

$1/2\ O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$

Sum:

$2\ H_2 + O_2 \rightarrow\ H_2O$ + energy

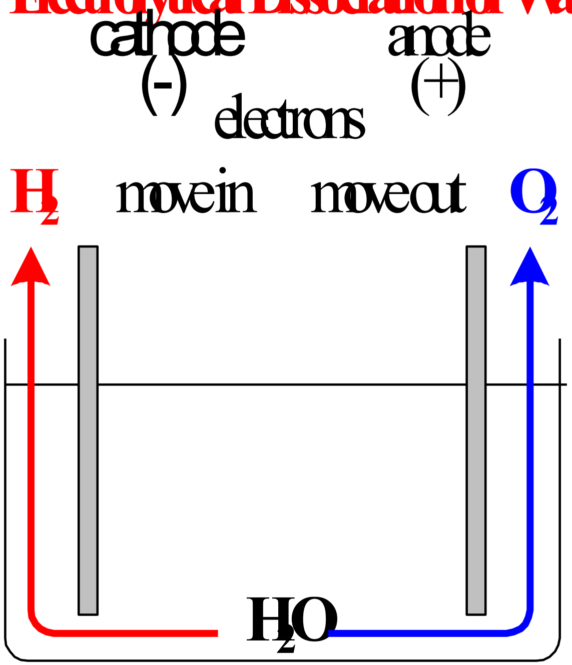
(voltage about 1 DCV)

Enthalpy of 286,2 kJ/mol H_2O is set free.

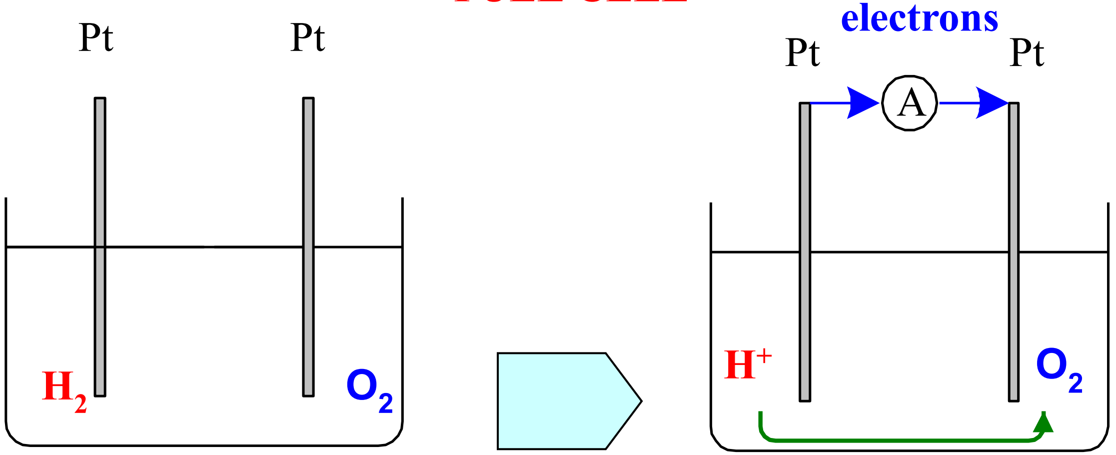
This reaction is called "Cold Combustion"

PHWien

Electrolytical Dissociation of Water



FUEL CELL

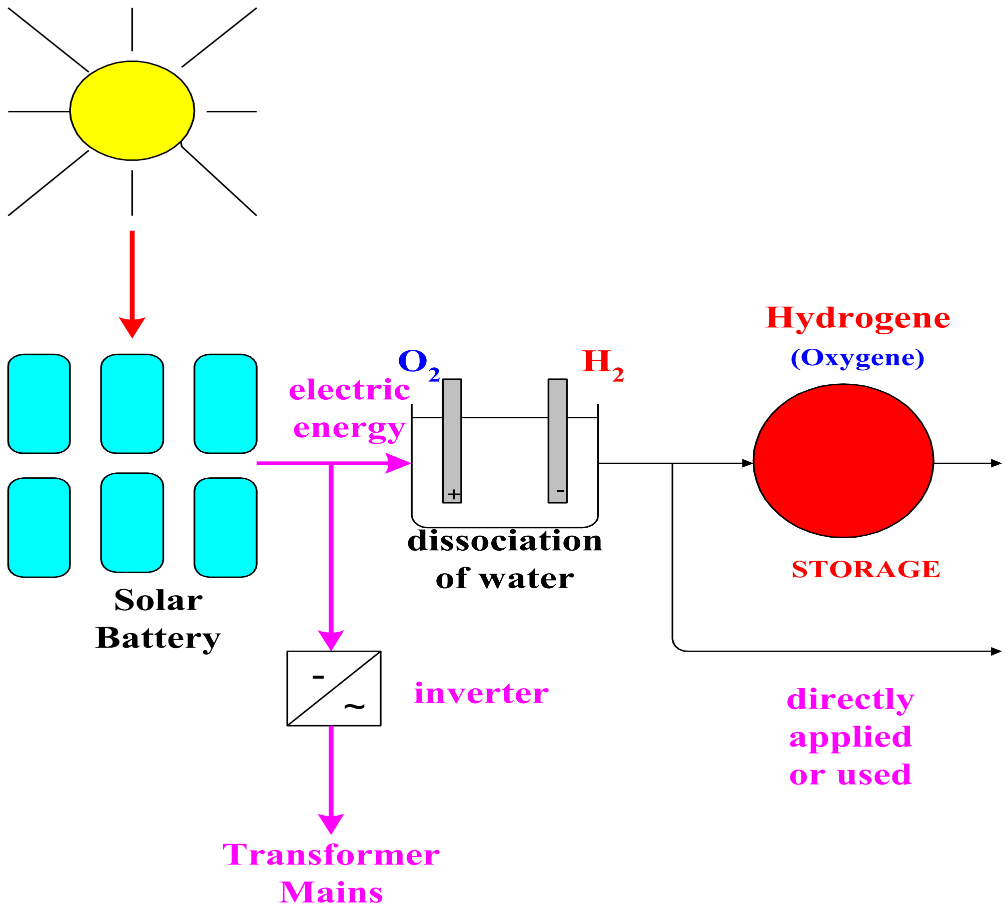


$H_2 \rightarrow 2\ H$

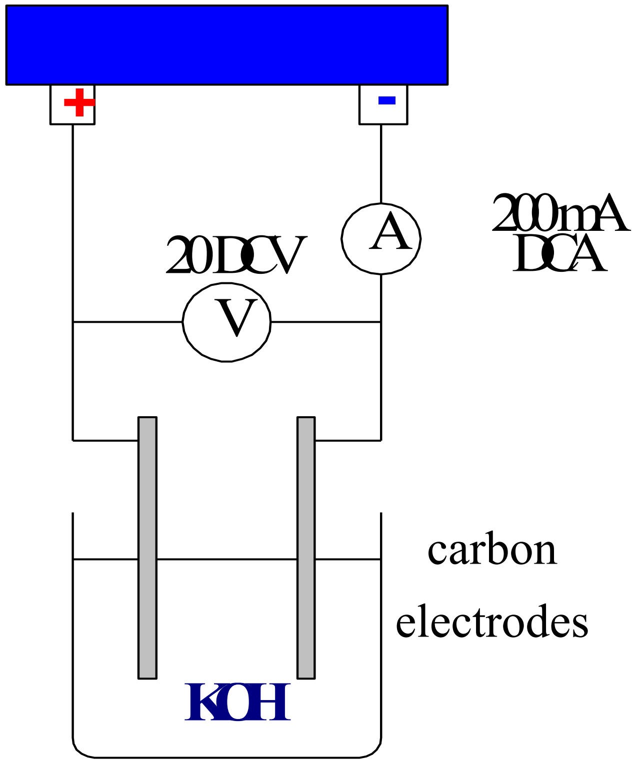
$2\ H \rightarrow 2\ H^+ + 2e^-$

$O_2 + 4H^+ + 4e^- \rightarrow 2\ H_2O$

Solar Hydrogene System



Basic Experiment to Hydrogene Technology

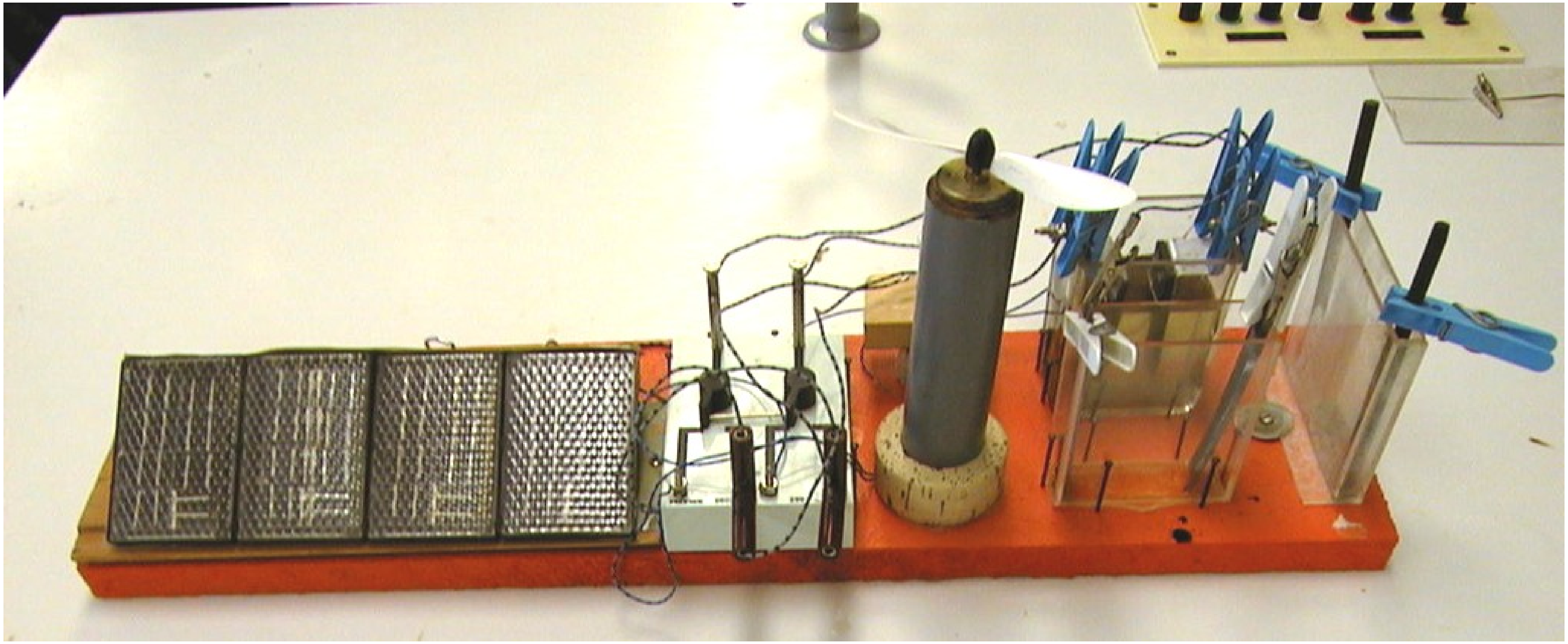


Potassium hydroxide solution (6 m):
11 g sodium hydroxide pastilles to 100 ml water

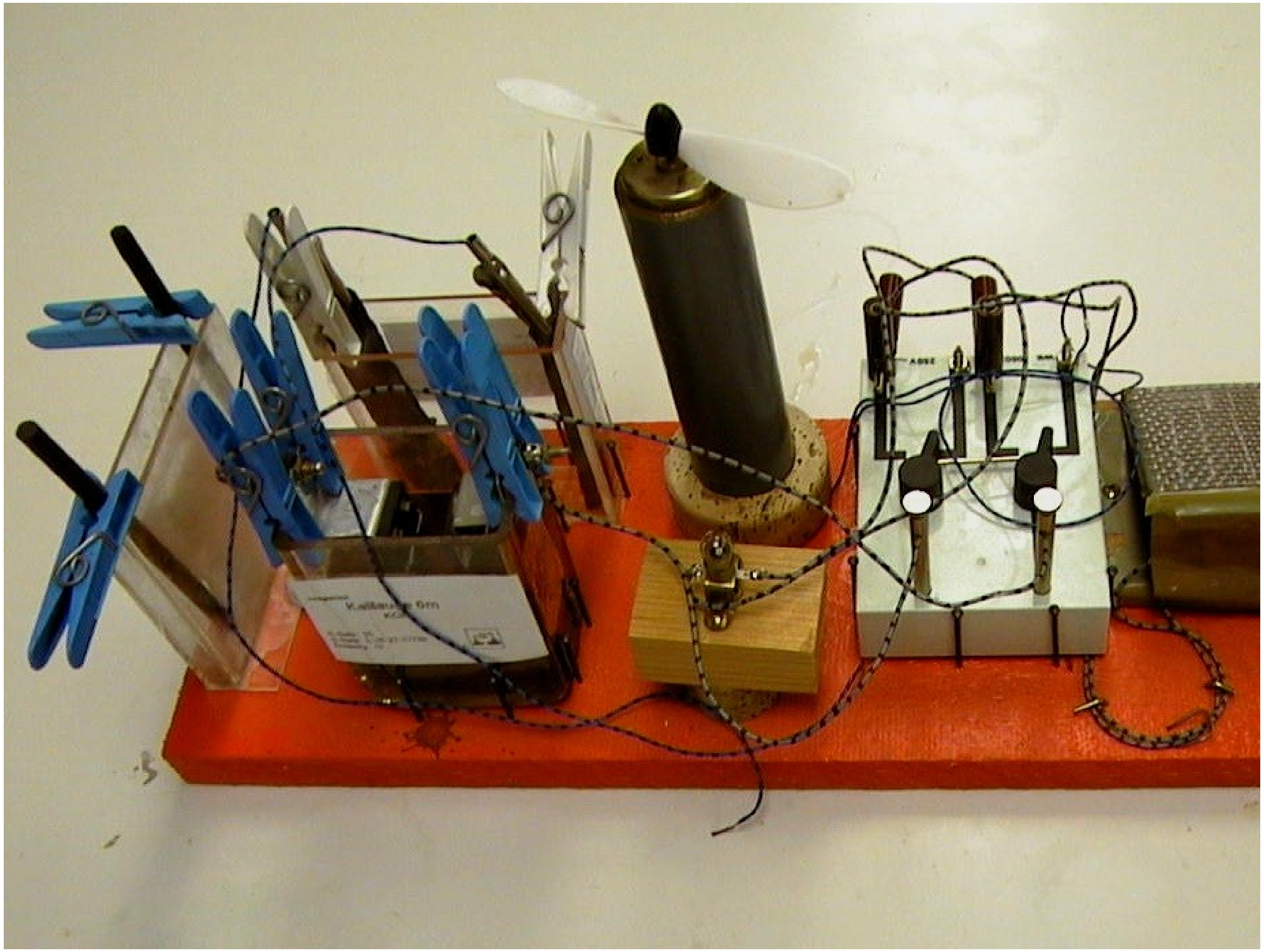
- Expose the solar battery to the sun.
- Observe the gasing - hydrogene and oxygene are developed.
- After about 10 minutes: separate the solar cell and connect the engine to the carbon electrodes.
- Read U and I.
- Observation:
  The electric motor firstly runs with high speed, after about one minute with low speed.
- Voltage and intensity of current are going down.

Photovoltaic generated hydrogene is turned to energy by means of the FUEL CELL. By this process electric energy is produced.

Basic Experiment „Hydrogene Technology“



Basic Experiment „Hydrogene Technology“



Calculating the Efficiency

Note:
You have to average all values of voltage and intensity of current in calculating the energy the engine has taken.

Fuel Cell	Fill in	Result	Comment
Irradiance in W/m²		0	
Length of the solar cell in cm			
Width of the solar cell in cm		0	A in m²
Power irradiated to the solar cell		0	P in W
Time of exposition in min		0	t in h
Engine			
Starting voltage in V		0	U in V
Intensity of Current in mA		0	I in A
End voltage in V		0	U in V
Power of the engine in Watt		0	P_1 in W
Time of running the motor in min		0	t in h
Efficiency		kA	

It should be something about some percents...