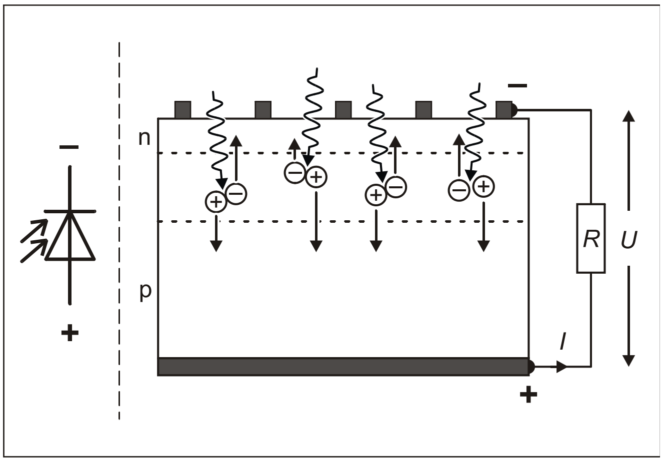
Recording the current-voltage characteristics of a solar battery as a function of the irradiance

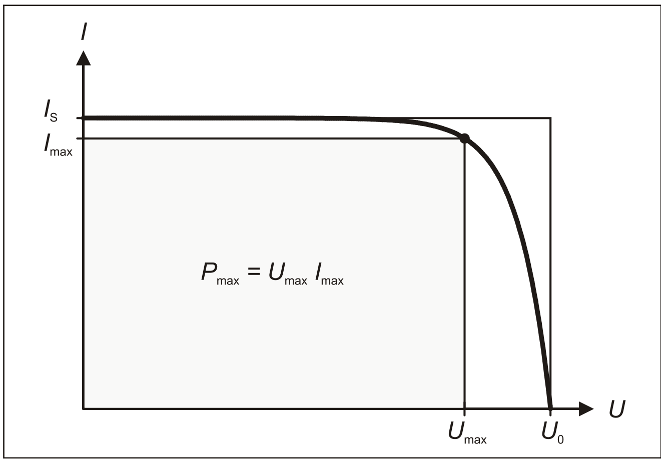
Objects of the experiment

- Recording the current-voltage characteristic point by point and measuring the open-circuit voltage U_0 and the short-circuit current I_S for various values of the irradiance.
- Determining the power P supplied as a function of the load resistance R for various values of the irradiance.
- Determining the maximum power P_{max}, the associated load resistance R_{max} and the fill factor.

Principles

A solar cell is a semiconductor component at whose p/n transition the radiation energy of incoming sun light is directly converted into electrical energy. The semiconductor component is a photodiode with a large surface area constructed so that the light can penetrate the p/n transition through a thin n or p conducting layer (see Fig. 1) and then creates electron-hole pairs. These are separated by the intrinsic electric field in the barrier layer and can migrate in the reverse direction. Electrons migrate into the n-doped region, and the holes migrate into the p-doped region.





If the external metal contacts are shorted, a short-circuit current I_S flows in the reverse direction of the photodiode. This current is substantially proportional to the number of electron-hole pairs created per unit time, i.e. it is proportional to the irradiance of the incoming light and the surface area of the solar cell. If the metal contacts are open, this reverse current leads to a open-circuit voltage U_0, which in turn leads to an equal diffusion current I_D in the forward direction of the diode so that no current flows at all. If a load with an arbitrary resistance R is connected, the current I flowing through the load depends on the resultant voltage U between the metal contacts. In a simplified manner, in can be considered to be the difference between the current I_S in the reverse direction, which depends on the irradiance Φ, and the current I_D of the non-irradiated semiconductor diode in forward direction, which depend on the terminal voltage U:

$$I = I_S(\Phi) - I_D(U) \qquad \text{(I).}$$

In this way, the current-voltage characteristics typical of a solar cell are obtained (see Fig. 2). In the case of small load resistances, the solar cell behaves like a constant-current source as the forward current I_D can be neglected. In the case of greater load resistances, the behaviour corresponds approximately to that of a constant-voltage source because then the current $I_D(U)$ increases quickly if the voltage changes slightly.

Fig. 1 Principle of operation of a solar cell

Fig. 2 Current-voltage characteristic of a solar cell for a given irradiance (U_{max}, I_{max}: point of maximum power)

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Apparatus

1 solar cell, 2 V / 0.3 A, STE 4/100		578 63
1 plug-in board A4		576 764
1 pair of board holders		576 77
1 potentiometer 220 Ω, 3 W, STE 2/19		577 90
1 set of ten bridging plugs		501 48
1 voltmeter, DC, $U \leq 10$ V	e. g.	531 120
1 ammeter, DC, $I \leq 3$ A	e. g.	531 120
1 halogen lamp housing,12 V, 50/100 W		450 64
1 incandescent lamp 12 V, 100 W		450 63
1 transformer 2 to 12 V		521 25
1 saddle base		300 11
Connecting leads		

At a fixed irradiance, the power supplied by the solar cell depends on the load resistance R. The solar cell reaches its maximum power P_{max} at a load resistance R_{max} which, to a good approximation, is equal to the so-called internal resistance

$$R_i = \frac{U_0}{I_S} \quad \text{(II).}$$

This maximum power is smaller than the product of the open-circuit voltage and the short-circuit current (see Fig. II). The ratio

$$F = \frac{P_{max}}{U_0 \cdot I_S} \quad \text{(III)}$$

is often called fill factor.

Often several solar cells are combined to form a solar battery. Series connection leads to a greater open-circuit voltage U_0, whereas parallel connection leads to a greater short-circuit current I_S. In the experiment, a series connection of four solar cells is set up, and the current-voltage characteristics are recorded for four different values of the irradiance. The irradiance is varied by changing the distance of the light source.

In addition, the power

$$P = U \cdot I \quad \text{(IV)}$$

supplied by the solar cell is displayed as a function of the load resistance

$$R = \frac{U}{I} \quad \text{(V).}$$

Setup

The experimental setup is illustrated in Fig. 3.

- Plug the STE solar cell into the plug-in board, and connect the upper negative pole to the lower positive pole using two bridging plugs (series connection of four solar cells).
- Plug in the STE potentiometer as a variable resistor, and connect it to the solar battery using bridging plugs.
- Connect the ammeter in series with the solar battery and the variable resistor. Select the measuring range 100 mA DC.
- Connect the voltmeter in parallel to the solar battery, and select the measuring range 3 V DC.
- Connect the halogen lamp to the transformer, and align it so that the solar battery is uniformly irradiated.

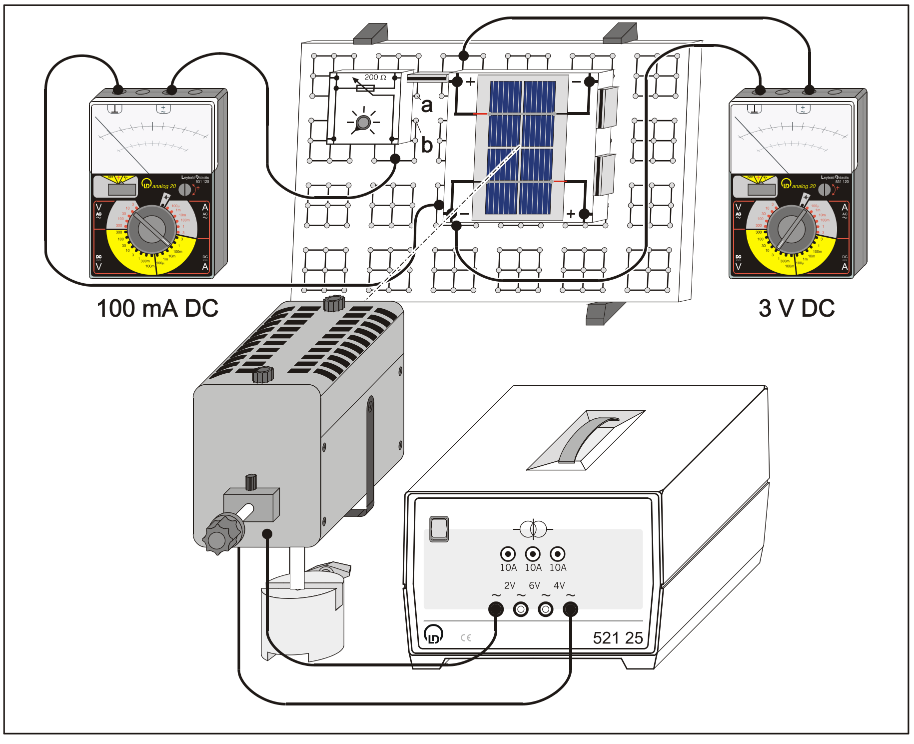

Fig. 3 Experimental setup for recording the current-voltage characteristics of a solar battery as functions of the irradiance

Carrying out the experiment

- Close the circuit, first shorting the variable resistor with an additional bridging plug between the points **a** and **b**, and choose the distance of the halogen lamp so that the short circuit current is approximately 100 mA.
- Remove the shorting bridging plug, and increase the terminal voltage or decrease the current, respectively, step by step by changing the load resistance. For each step read the current and the voltage, and take them down.
- Then interrupt the circuit, and measure the open-circuit voltage.

- Adjust a short-circuit current of approximately 75 mA – and after that 50 mA and 25 mA – by increasing the distance of the halogen lamp, and repeat the series of measurements.

Measuring example

Table 1: measured values of the terminal voltage *U* of the solar battery and the current *I* flowing through the load resistor.
* Short-circuit current $I_{S,}$ $^{+}$ Open-circuit voltage U_0

← minimum			irradiance				maximum →
Meas. series 4		Meas. series 3		Meas. series 2		Meas. series 1	
$\frac{U}{V}$	$\frac{I}{mA}$	$\frac{U}{V}$	$\frac{I}{mA}$	$\frac{U}{V}$	$\frac{I}{mA}$	$\frac{U}{V}$	$\frac{I}{mA}$
0.02	25.5 *	0.05	50.0 *	0.04	74.0 *	0.06	100.0 *
0.25	25.5	0.25	50.0	0.20	73.5	0.24	99.5
0.50	25.5	0.50	50.0	0.50	73.0	0.50	99.5
0.75	25.0	0.82	50.0	0.75	73.0	0.75	99.0
1.00	25.0	1.05	50.0	1.00	72.5	1.00	99.0
1.10	25.0	1.20	49.5	1.10	73.0	1.10	99.5
1.20	25.0	1.35	49.5	1.25	73.0	1.20	99.0
1.30	24.5	1.45	49.0	1.40	73.0	1.35	99.5
1.40	24.0	1.60	49.0	1.55	72.5	1.50	98.0
1.50	23.5	1.72	46.5	1.67	69.5	1.60	96.0
1.60	22.5	1.80	42.0	1.75	65.5	1.70	91.0
1.70	20.5	1.88	35.0	1.80	61.5	1.80	84.0
1.80	16.5	1.92	30.0	1.85	56.0	1.85	78.0
1.85	13.0	1.95	20.0	1.90	50.0	1.90	66.5
1.88	10.0	2.01	10.0	1.95	40.0	1.95	57.0
1.96 +	0.0	2.04 +	0.0	1.98	30.0	1.98	50.0
—	—	—	—	2.02	20.0	2.01	40.0
—	—	—	—	2.04	10.0	2.04	30.0
—	—	—	—	2.07 +	0.0	2.06	20.0
—	—	—	—	—	—	2.08	10.0
—	—	—	—	—	—	2.10 +	0.0

Evaluation

Table 2: values of *P* and *R* calculated from the measured values of *U* and *I* from Table 1

← minimum			irradiance				maximum →
Meas. series 4		Meas. series 3		Meas. series 2		Meas. series 1	
$\frac{R}{\Omega}$	$\frac{P}{mW}$	$\frac{R}{\Omega}$	$\frac{P}{mW}$	$\frac{R}{\Omega}$	$\frac{P}{mW}$	$\frac{R}{\Omega}$	$\frac{P}{mW}$
0.8	0.5	1.0	2.5	0.5	3.0	0.6	6.0
9.8	6.4	5.0	12.5	2.7	14.7	2.4	23.9
19.6	12.8	10.0	25.0	6.8	36.5	5.0	49.8
30.0	18.8	16.4	41.0	10.3	54.8	7.6	74.3
40.0	25.0	21.0	52.5	13.8	72.5	10.1	99.0
44.0	27.5	24.2	59.4	15.1	80.3	11.1	109.5
48.0	30.0	27.3	66.8	17.1	91.3	12.1	118.8
53.1	31.9	29.6	71.1	19.2	102.2	13.6	134.3
58.3	33.6	32.7	78.4	21.4	112.4	15.3	147.0
63.8	35.3	37.0	80.0	24.0	116.1	16. 7	153.6
71.1	36.0	42.9	75.6	26.7	114.6	18.7	154.7
82.9	34.9	53.7	65.8	29.3	110.7	21.4	151.2
109.1	29.7	64.0	57.6	33.0	103.6	23.7	144.3
142.3	24.1	97.5	39.0	38.0	95.0	28.6	126.4
188.0	18.8	201.0	20.1	48.8	78.0	34.2	111.2
—	—	—	—	66.0	59.4	39.6	99.0
—	—	—	—	101.0	40.4	50.3	80.4
—	—	—	—	204.0	20.4	68.0	61.2
—	—	—	—	—	—	103.0	41.2
—	—	—	—	—	—	208.0	20.8

Table 3: load resistance R_{max} corresponding to the maximum power and internal resistance R_i calculated according to Eq. (II)

	← minimum	irradiance		maximum →
	Meas. series 4	Meas. series 3	Meas. series 2	Meas. series 1
$\frac{R_{max}}{\Omega}$	71.1	37.0	24.0	18.7
$\frac{R_i}{\Omega}$	76.9	40.8	28.0	21.0
$\frac{R_{max}}{R_i}$	0.92	0.91	0.86	0.89

Table 4: maximum power P_{max} and product of the open-circuit voltage and the short-circuit current

	← minimum	irradiance		maximum →
	Meas. series 4	Meas. series 3	Meas. series 2	Meas. series 1
$\frac{P_{max}}{mW}$	36.0	80.0	116.1	154.7
$\frac{U_0 \cdot I_S}{mW}$	50.0	102.0	153.2	210
$\frac{P_{max}}{U_0 \cdot I_S}$	0.72	0.78	0.76	0.74

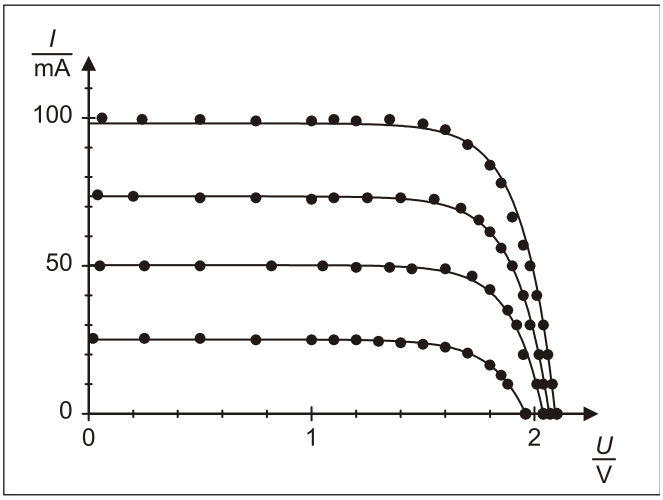

Fig. 4 Current-voltage characteristics of the solar battery measured for four different values of the irradiance

Current-voltage characteristics:

Fig. 4 shows the current-voltage characteristics obtained from the measured values (see Table 1). It is seen that, at a small load resistance *R*, i.e. at a low terminal voltage *U*, the solar battery supplies a constant current, which is obviously dependent on the irradiance. When the voltage drops below a certain value, which depends to a less extent on the irradiance, the solar battery works approximately as a constant-voltage source.

The curves drawn in the diagram were calculated under the simplifying assumption that the current *I* is given by the difference of the irradiance-dependent reverse current and a forward current, which depends on the terminal voltage (see Eq. (I)).

The open-circuit voltage of the solar battery is approximately 2 V. As the solar battery is the result of a series connection of four equal solar cells, the open-circuit voltage of a single solar cell is approximately 0.5 V.

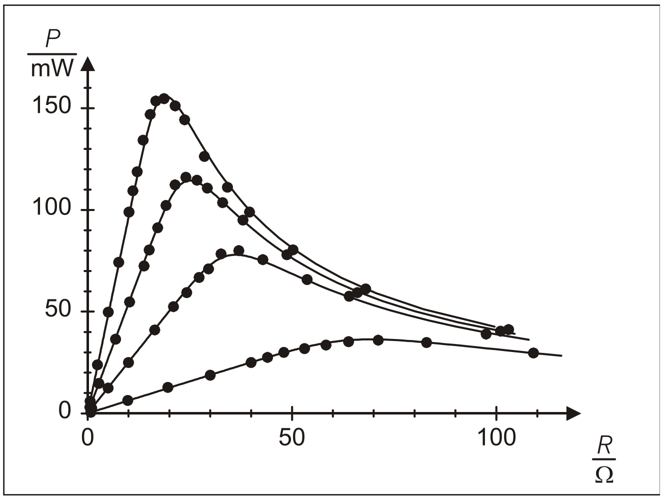

Fig. 5 Power-load resistance characteristics of the solar battery for four different values of the irradiance

Power-load resistance characteristics:

In Table 2, the values of the power *P* supplied and the load resistance *R* calculated from the measured values of *U* and *I* from Table 1 according to Eqs. (IV) and (V) are listed. Fig. 5 shows a plot of the values from the table.

When the load resistance *R* is small, *P* increases at a given irradiance linearly with *R* because the solar battery behaves like a constant-current source. For greater load resistances, *P* is inversely proportional to *R* because now the solar battery corresponds approximately to a constant-voltage source.

The load resistance R_{max}, at which the power supplied reaches its maximum, becomes smaller when the irradiance increases. The corresponding values are listed in Table 3 together with the internal resistances R_i, which are calculated according to Eq. (II).

Table 4 contains a list of the maximum power values. They increase with increasing irradiance. The fill factor defined in Eq. (III) is approximately 75 % for this solar battery.

Result

In a solar cell (solar battery), the short-circuit current clearly depends on the irradiance (linearly). The dependence of the open-circuit voltage on the irradiance is weaker (logarithmically).

For small load resistances, the solar cell behaves like a constant-current source, whereas for great load resistances it behaves like a constant-voltage source.

The power supplied at a given load resistance also depends on the irradiance. The maximum power is supplied at a load resistance which is approximately equal to the internal resistance of the solar cell and which decreases with the irradiance.