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.

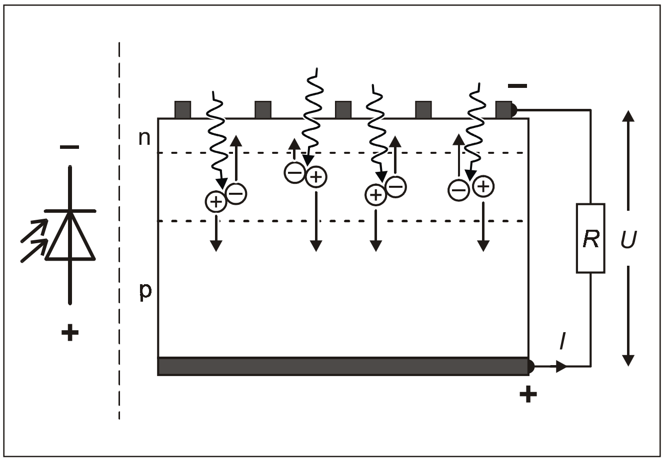

Fig. 1 Principle of operation of a solar cell

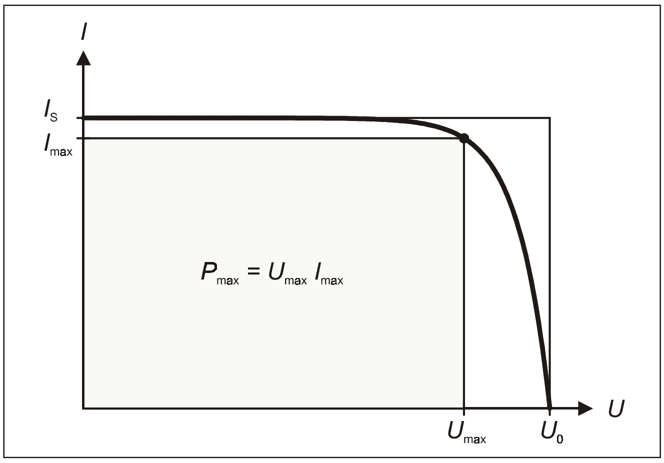

Fig. 2 Current-voltage characteristic of a solar cell for a given irradiance (U_{max}, I_{max}: point of maximum power)

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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.

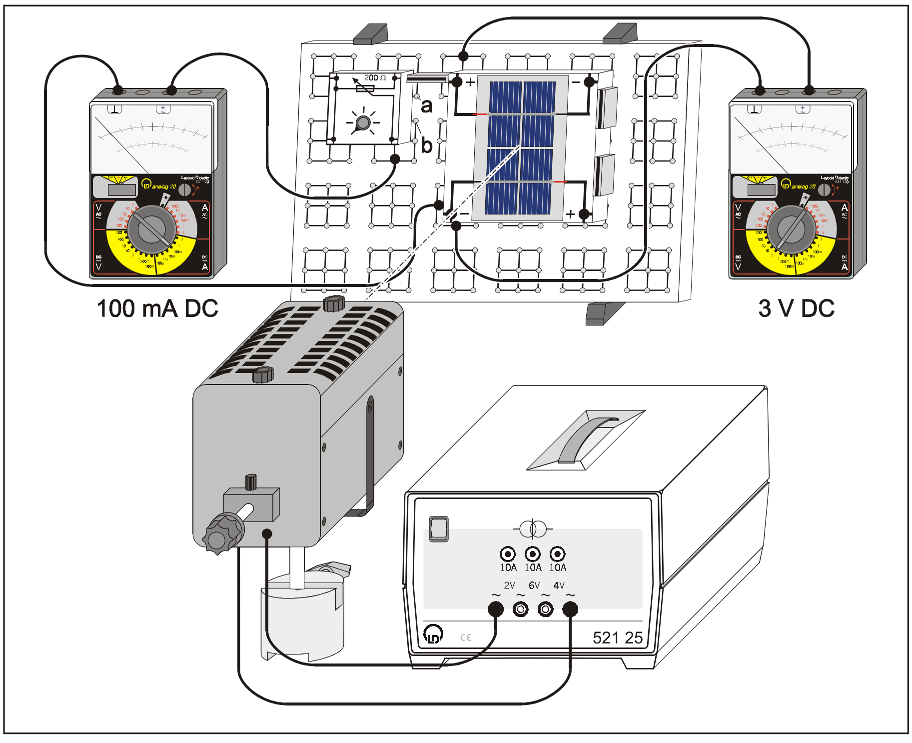

Fig. 3 Experimental setup for recording the current-voltage characteristics of a solar battery as functions of the irradiance

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	
U / V	I / mA	U / V	I / mA	U / V	I / mA	U / V	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	
R / Ω	P / mW	R / Ω	P / mW	R / Ω	P / mW	R / Ω	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
$\frac{P_{max}}{W}$	36.0 W	80.0 W	116.1 W	154.7 W
$\frac{U_0 \cdot I_S}{W}$	50.0 W	102.0 W	153.2 W	210 W
$\frac{P_{max}}{U_0 \cdot I_S}$	0.72	0.78	0.76	0.74

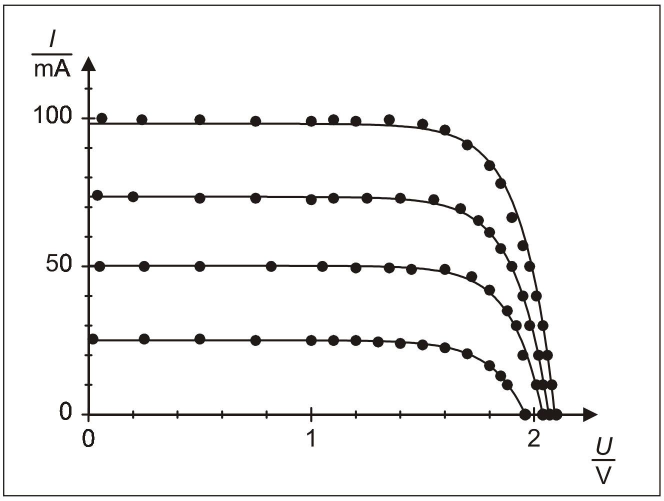

Fig. 4 Current-voltage characteristics of the solar battery measured for four different values of the irradiance

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.

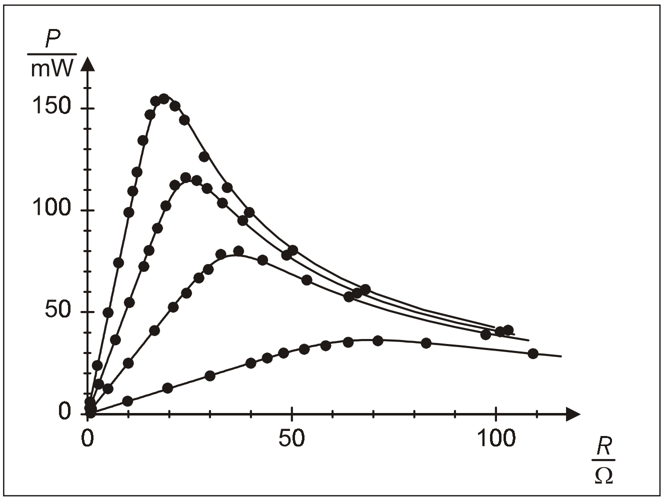

Fig. 5 Power-load resistance characteristics of the solar battery for four different values of the irradiance

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.

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Related Topics

Semi-conductor, p-n junction, energy-band diagram, Fermi characteristic energy level, diffusion potential, internal resistance, efficiency, photo-conductive effect, acceptors, donors, valence band, conduction band.

Principle

To measure the current-voltage characteristics of a solar cell at different light intensities, the distance between the light source and the solar cell is varied. Moreover, the dependence of no-load voltage on temperature is determined.

Equipment

1	Solar battery, 4 cells, 2.55 cm	06752.04	2	Support rod -PASS-, square, l = 250 mm	02025.55
1	Thermopile, molltype	08479.00	2	Right angle clamp -PASS-	02040.55
1	Universal measuring amplifier	13626.93	1	Plate holder	02062.00
1	Rheostat, 330 Ohm, 1.0 A	06116.02	1	Universal clamp	37715.00
1	Lamp socket E27, mains conn.	06751.00	2	Bench clamp -PASS-	02010.00
1	Filament lamp, 220 V/120 W, w. refl.	06759.93	1	Glass pane, 1501004 mm, 2 off	35010.10
1	Hot-/Cold air blower, 1700 W	04030.93	2	Digital multimeter	07134.00
1	Meter scale, demo, l = 1000 mm	03001.00	1	Lab thermometer, -10...+100°C	38056.00
2	Tripod base -PASS-	02002.55	3	Connecting cord, l = 500 mm, red	07361.01
2	Barrel base -PASS-	02006.55	2	Connecting cord, l = 500 mm, blue	07361.04

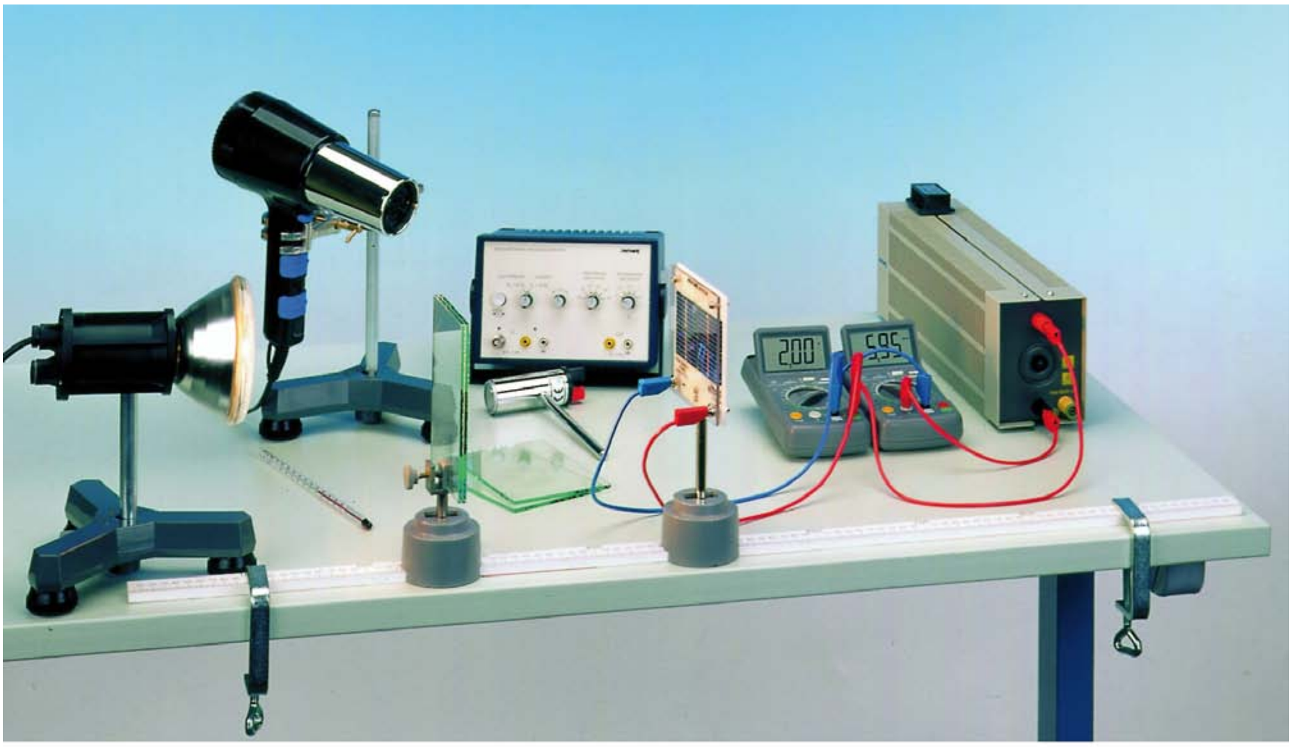

Fig. 1: Set-up of experiment P2410901

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Tasks

1. Measure the short-circuit current and no-load voltage at different light intensities and plot the current-voltage characteristic at different light intensities.
2. Estimate the dependence of no-load voltage and short-circuit current on temperature.
3. Plot the current-voltage characteristic under different operating conditions: cooling the equipment with a blower, no cooling, shining the light through a glass plate.
4. Determine the characteristic curve when illuminating by sunlight.

Set-up and Procedure

- The thermopile only measures the light of the lamp but the solar cell also detects the diffused light coming from reflections on the bench top. Therefore, it is recommended to cover the bench with a black cloth or piece of black card to suppress the diffused light.
- The experimental set-up is as shown in Fig. 1. The glass plate is only needed for task 3.
- Do the electrical connections as in Fig. 2

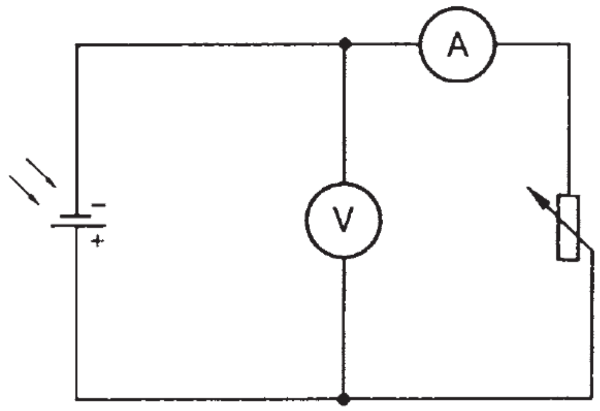

Fig. 2: Circuit for measuring the current-voltage characteristic.

Task1

The light intensity is varied by varying the distance between the light source and the solar cell. First of alle, measure the light intensity with the thermopile and amplifier with the equipment at different distances from the light source. (**Note:** the maximum output voltage of the amplifier is 10 V). The inlet aperture marks the position of the thermopile. The distance between the lamp and the thermopile should be at least 50 cm, since the angular aperture of the thermopile is only 20°.

To suppress the influence of the temperature on the characteristics of the solar cell, keep it at room temperature with the aid of the cold air blower during the experiment.

Task 2

To demonstrate the temperature effect, blow hot air over the solar cell and measure the temperature directly in front of it with a thermometer. Do not touch the cell as its thin p-layer can easily be damaged.

We recommend separating the lamp and solar cell more than 50 cm, because in shorter distances the temperature rise caused by radiation could falsify the measurement. Measure the noload voltage and the short-circuit current.

Task 4

- The characteristics of the solar cell should be measured in sunlight also if possible; in this case both direct and diffused light are involved.
- The thermophile is used again to determine the relationship between the short-circuit current and the light intensity, although it measures only direct light because of its small angular aperture. For comparative purposes, therefore, we must support a black cardboard tube about 20 cm long in front of the solar cell to screen it from the diffused light. It is important that the thermopile and the solar cell are pointing directly into the sun.

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Theory and evaluation

Pure silicon is deliberately 'impurified' (doped) with tri- and pentavalent impurity atoms to make a p- or n-type semi-conductor. If we put a p-and n-type crystal together we get a junction (pn-junction, Fig. 3) whose electrical properties determine the performance of the solar cell.

In equilibrium (with no external voltage) the Fermi characteristic energy level E_F will be the same throughout. Because of the difference in the concentrations of electrons and holes in the p- and n-regions, electrons diffuse into the p-region and holes into the n-region. The immobile impurity atoms create a space charge-limited current region; the diffusion current and the field current offset one another in equilibrium.

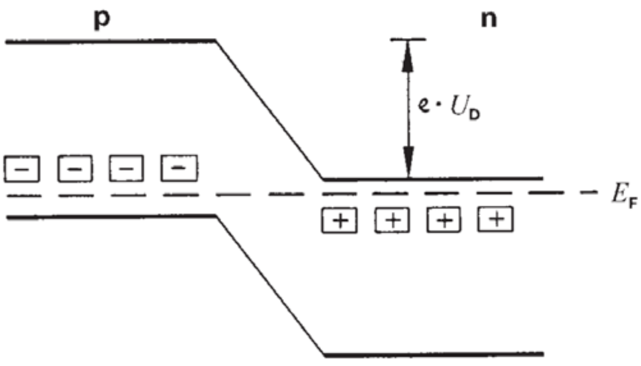

Fig. 3: pn-junction in the energy-band diagram – acceptors, + donors, U_D is the diffusion potential, E_F is the Fermi characteristic energy level, and e is the elementary charge.

The diffusion potential U_D in the pn-junction depends on the amount of doping and corresponds to the original difference between the Fermi energy levels of the separate p- and n-regions.

The distance between the valence band and the conduction band in silicon at room temperature is

E = 1.1 eV

For silicon, the diffusion potential is

U_D = 0.5 to 0.7 V.

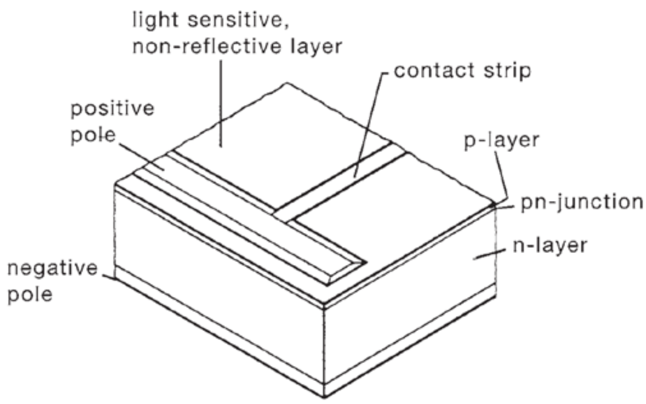

Fig. 4: Construction of a silicon solar cell.

If light falls on the pn-junction, the photons create electronhole pairs separated by the space charge. The electrons are drawn into the n-region and the holes into the p-region. Photons are absorbed not only in the pn-junction but also in the p-layer above it. The electrons produced are minority carriers in those areas: their concentration is greatly reduced by recombination and with it their efficiency. The p-layer must therefore be sufficiently thin for the electrons of diffusion length L_E to enter the n-layer.

$L_E >> t$,

where t = thickness of p-layer.

If g is the number of electron-hole pairs produced per unit area and of a voltage U is applied across the pn-junction, a stream of electrons and holes of density

$$i = e \cdot \left(e^{eU/kT} - 1\right)\left(\frac{n_0 D_e t}{L^2{}_e} + \frac{p_0 D_h}{L_h}\right) - eg \quad (1)$$

is produced, where e is the elementary charge, k is Boltzmann's constant, T is the temperature, L is the diffusion length of electrons and holes, D is the diffusion constant for electrons and holes, n_0 and p_0 are equilibrium concentrations of the minority carriers.

The short-circuit current density (U = 0)

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$$i_s = -e \cdot g$$

is proportional to the intensity of the incident light at fixed temperature. g becomes very slightly greater (less than 0.01 %/K) as the temperature rises.

The voltage U can become as high as the diffusion potential U_D but no higher. As the temperature rises the no-load voltage decreases typically by –2.3 mV/K, since the equilibrium concentrations n_0 and p_0 increase with the temperature:

$$n_0 \sim e^{-\frac{\Delta E}{2kT}}$$

Task 1:

For this task, it is assumed that all the light entering the aperture (dia. 2.5 cm) reaches the measuring surface. The sensitivity is 0.16 mv/mW. Plotting the light intensity J over the distance s gives a straight line. By extrapolating the straight line we can determine the intensity at distances $s \leq 50$ cm.

Fig 6 shows the relationship between the light intensity and the short-circuit current and no-load voltage (Fig. 6).

The solar battery which consists of four cells connected in series thus has a maximum no-load voltage of 2 V. The shortcircuit current is proportional to the light intensity.

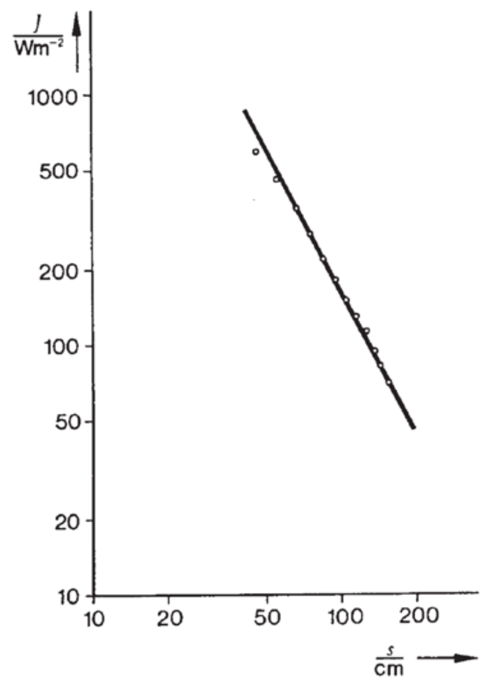

Fig. 5: Light intensitiy J at distances s normal to the light source.

$$I_s = 1.84 \cdot 10^{-4} A/Wm^{-2} \cdot J$$

The current-voltage characteristic at different light intensities J is shown in Fig. 7. The maximum power output is at the turning points on the curves (joined by the broken line; Fig. 7) at which the load resistor has the same value as the internal resistance R_i of the solar battery.

The internal resistance decreases with increasing light intensity. If we compare the maximum power output with the incident power, we obtain an efficiency of approx. 6% (area of solar battery 50 cm^2).

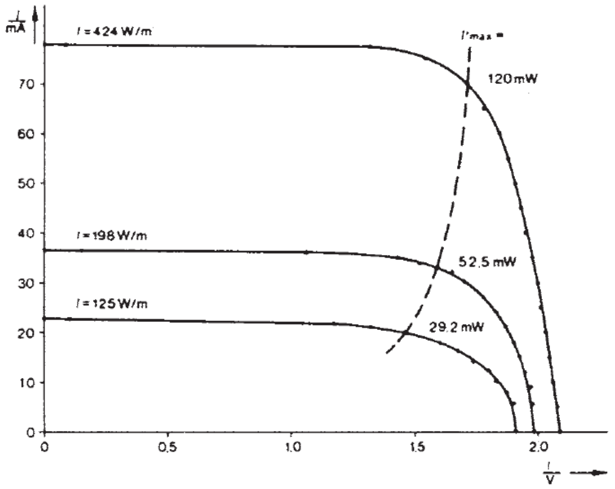

Fig. 7: Current-voltage characteristic at different light intensities J.

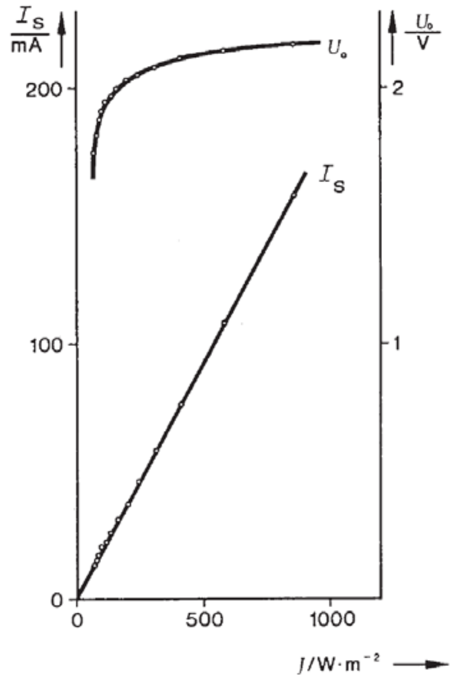

Fig. 6: Short-circuit current I_s and no-load voltage U_0 as a function of the light intensity J.

Task 2:

Measuring the effect of temperature on U_0 and I_s the temperature distribution over the hot air area must be taken into account. The measurements can provide only a rough order of magnitude of this. Measuring the no-load voltage with hot and cold air gave:

$$\frac{\Delta U_0}{\Delta T} = -8mV/K$$

We thus obtain the value –2 mV/K for one cell.

The change in short-circuit current with the temperature cannot be measured.

Task 3:

A glass plate which absorbs light in the infrared region can be used to reduce a rise in temperature of the solar battery. Fig. 8 shows the effect of the various 'operating modes'.

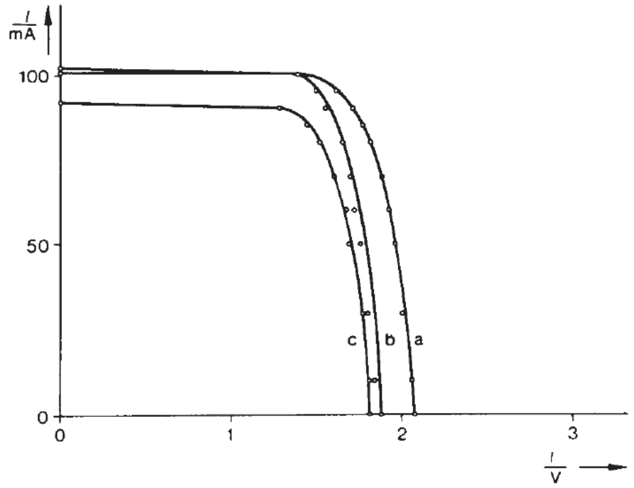

Fig. 8: Current-voltage characteristics of the solar battery
a) with blower cooling
b) with no blower cooling
c) when screened with a glass plate.

Task 6:

Sunlight incident on solar cells produces different characteristic curves from incandescent light. The reason lies in the different spectra of the two light sources (Fig. 9). At the same light intensity, sunlight produces a higher shortcircuit current

$$I_s = 3.04 \cdot 10^{-4} \cdot JA/Wm^{-2}$$

Because the infrared region of the spectrum of sunlight is smaller, the solar cell does not heat up so much and the measurements with and without cooling provide the same characteristics for sunlight.

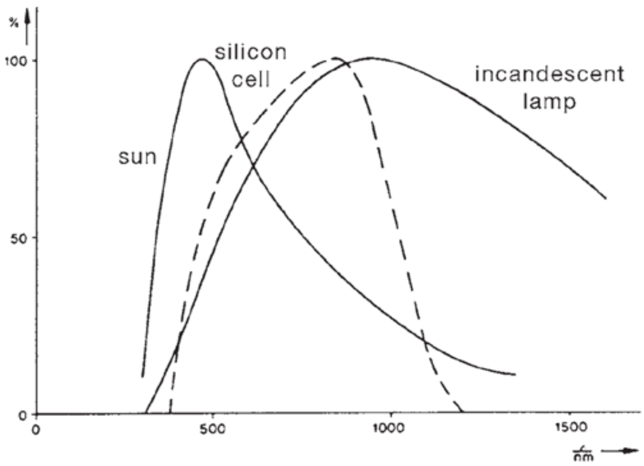

Fig. 9: Spectrum of the sun (T approx. 5800 K) and of an incandescent lamp (T appox. 2000 K), and the spectral sensitivity of the silicon solar cell.

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