Proceedings of "Applications of Physics in Mechanical and Material Engineering" (APMME 2024)

Basic Diagnostics of Electrical and Structural Properties of Solar Cells

M. Musztyfaga-Staszuk*

Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland

Doi: 10.12693/APhysPolA.147.270 *e-mail: malgorzata.musztyfaga@polsl.pl

In a single batch of base material for Si wafers from a single manufacturer, there are no two wafers with absolutely identical physical and material parameters. The production of a series of cells based on them in a specific technological process introduces further differences in the distribution of parameters. This results in variability of measured performance parameters of solar cells, which generally takes the form of a Gaussian distribution. A solar cell based on crystalline silicon features a large front surface area; for example, for a standard 6-inch single element produced in the photovoltaic industry, it amounts to 236 cm^2. During the technological process, the cell surface undergoes texturing, which increases its size by approximately 1.7 times in the case of a classic texture consisting of randomly distributed pyramids. Achieving a cell with high efficiency is determined by an internal quantum efficiency above 90%, which in turn requires that the doping concentration in the surface-near region cannot exceed 1.4×10^{20} atoms/cm^3. On the other hand, when using metallic contacts for the front electrode of the cell applied via screen printing with Ag paste, the doping concentration in the surface-near region cannot be lower than 10^{20} atoms/cm^3 to ensure a contact resistivity value at the level of a few mΩ cm^2. Operations carried out in the solar cell manufacturing technology, such as crystallization, doping of the base material, and particularly high-temperature processes, influence the carrier lifetime in the semiconductor in various areas of the cell. This lifetime is the sum of the components dependent on the carrier lifetime due to the processes of radiative recombination, Auger recombination, and recombination through trapping in different regions of the cell. The article presents the results of research on the electrical and structural properties of commercially available polycrystalline photovoltaic cells purchased from one of the manufacturers. The issues discussed and the investigations conducted contribute to a deeper understanding and characterization of the solar cell, while the proposed diagnostic tools pave the way for innovation by identifying problems that need to be addressed in the future, including the potential use of new materials.

topics: polycrystalline solar cells, electrical properties, diagnostics

1. Introduction

Humanity is struggling with many crises, and one of them is the energy crisis. Energy crisis is understood as a situation in which there is a significant shortage in energy availability, which leads to higher prices, supply constraints, and serious consequences for the economy and society. The energy crisis taking place around the world is related to many factors, such as climate change, rising prices of raw materials, political instability, and the ever-growing energy demand. Many strategies can help solve this problem (Fig. 1) [1].

The development of renewable energy sources is associated with increasing investments in solar, wind, hydroelectric, and biomass energy [1] and promoting technologies that enable more effective use of these sources. In the case of solar energy, it can be used in many ways and its applications are diverse (Fig. 2) [2].

A solar cell is a semiconductor element (device) that converts solar energy into electricity. The photovoltaic phenomenon occurs in a solar cell, and involves the generation of an electric current as a result of the absorption of sunlight by semiconductor materials, usually silicon. Solar cells consist of two semiconductor layers (usually n-type and p-type) that form a p–n junction. When sunlight hits the cell, photons with enough energy to excite electrons in the semiconductor material release them from their positions, leading to the formation of electron–hole pairs. The movement of these charges in the p–n junction generates an electric current that can be used to power electrical devices or charge batteries [3–7].

Silicon solar cells play a key role in the production of energy from renewable sources [8, 9]. Their efficiency and reliability are crucial for the efficiency of photovoltaic systems [10]. However, the world is striving to replace silicon with other materials. Many research centres carry out development works

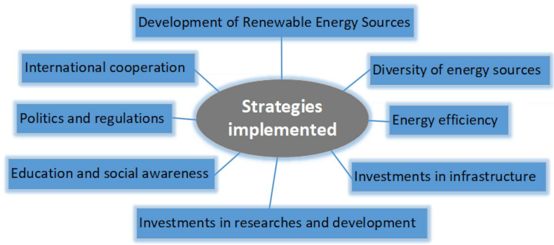

Fig. 1. Strategies used to solve the energy crisis.

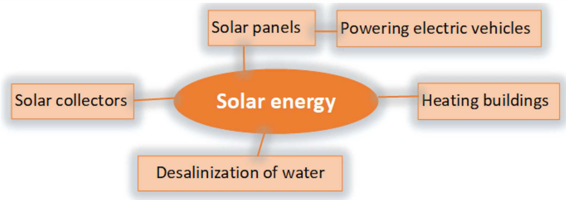

Fig. 2. Examples of the use of solar energy.

on the modernization of solar cell production technology and the materials used for their production. And why is this so? Researchers are looking for alternative materials to silicon in solar cells for several reasons, including [11, 12]:

i. Photovoltaic conversion efficiency — Although silicon solar cells are widely used, their maximum efficiency is about 26%. New materials, such as perovskites, have the potential to achieve higher efficiencies.

ii. Cost — Silicon used to produce solar cells is expensive. Alternative materials may be cheaper and easier to produce, which could lower the overall cost of already-built solar panels.

iii. Flexibility — Some new materials allow the production of flexible solar cells that can be used in a variety of applications, such as on curved surfaces or in coatings.

iv. Eco-friendliness — Some alternative materials may be more ecological than silicon in terms of production and recycling.

v. Availability of raw materials — Silicon is a common material, but its extraction and processing may involve certain limitations. Exploring alternative materials, such as organic materials or other minerals, can reduce dependence on silicon.

iv. Technological innovations — Ongoing research into new materials stimulates the development of photovoltaic technologies and the creation of new solutions that can improve the efficiency and adaptability of solar cells.

Basic diagnostics of solar cells for use in photovoltaic (PV) panels are crucial to assessing their performance and durability. Here are some key issues to consider when diagnosing solar cells [13, 14]:

- Product defects — They may result from errors during the manufacturing process, such as incorrect semiconductor material, contaminants on the cell surface, or structural defects.
- Defects related to assembly — Incorrect connections, mechanical damage, or incorrect positioning of the cell in the system may affect its conversion efficiency.
- Environmental disadvantages — Extreme weather conditions, such as heavy rain, snow, or high temperatures, may lead to degradation of materials and, consequently, loss of conversion efficiency of solar cells.

The diagnostics of defects in solar cells consist in a variety of methods that enable the identification of problems. These include:

i. Visual inspection [15]
   - Check for damage — Paying attention to any cracks, chips, or discoloration on the surface of the cells.
   - Pollution — Checking for the presence of dirt, dust, sand, or leaves that may affect the conversion efficiency of solar cells.
   - Corrosion — Checking the electrical connections and the panel housing for corrosion.

ii. Thermal inspection [16]
   - Using a thermal camera to detect hot spots that may indicate problems with the solar cells (e.g., improper contact, internal damage).

iii. Investigations of electrical parameters, including [17, 18]
   - Checking the current–voltage (I–V) characteristics. This can be done using a sunlight simulator, which allows one to assess whether the cells are operating according to their specifications.
   - Measuring the insulation resistance of AC (alternating current) and DC (direct current) cables, which allows one to determine if the wires have been cut somewhere along the cable route.

iv. Performance analysis [19]
   - Analyzing panel performance data under various sun exposure conditions to determine if the results achieved are as expected based on manufacturer's specifications.

v. Regular maintenance [20]
   - Cleaning and maintenance — Regularly cleaning and servicing the panels to ensure optimal performance.
   - Leak testing — Ensuring the panel is airtight to prevent damage from water or moisture.

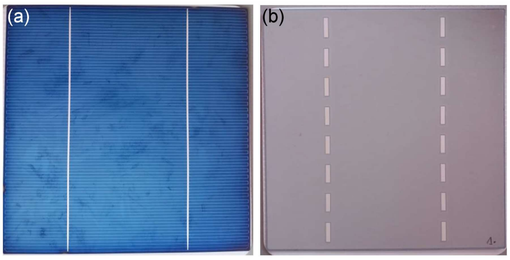

Fig. 3. Multicrystalline solar cell: (a) front, (b) back (example).

vi. Use of modern diagnostic methods (with technological progress, diagnostic techniques are also developing), which increasingly use artificial intelligence (AI) and data analysis, which allows for faster and more precise diagnosis of defects [21].

- Drones with thermal imaging cameras — They enable quick and effective viewing of large areas of solar installations, making it much easier to detect problems.

Solar cells are a fundamental element in the development of renewable energy sources. Their efficiency and reliability are crucial for the efficiency of photovoltaic systems. However, like any device, these cells may have defects that affect their functioning. Diagnosing defects in solar cells is therefore an important process that allows for the identification and solving of problems, which in turn leads to the optimization of their operation. In this article, we analyze in laboratory conditions the electrical properties of individual solar cells purchased from one of the manufacturers to detect technical problems, which allows for minimizing potential financial losses related to non-functioning or inefficient cells. The analyzed cells are then installed in panels. Installations must meet certain standards and regulations, and diagnostics help to ensure compliance with these requirements.

Diagnosing defects in solar cells is of great importance not only for the efficiency of individual modules, but also for entire photovoltaic systems. Early identification of problems allows them to be solved quickly, which reduces energy and financial losses. Regular inspections and diagnostics can significantly extend the life of the installation and improve its overall efficiency.

2. Research material

As part of the experiment, 30 first-generation solar cells were purchased from an industrial manufacturer. The cells were divided into three series (I, II, III), of which 3 cells were randomly selected for each series. The wafers had a thickness of 180 ± 10 μm and a surface of 15.6×15.6 cm^2. Silver paste was used to create the front metallization, a paste with bismuth glaze and the addition of aluminum were used for the rear connection contact, and aluminum paste for the rear contact (Fig. 3).

3. Research methodology

Measurements of the electrical properties of the investigated solar cells were performed using:

i. Measuring station equipped with the Corescan device — The equipment was designed by SunLab. Two modes of computer software were used during the research, i.e., Core scan (Contact Resistance Scan) and LBIC (Light Beam Induced Current). In the first mode, the potential differences (PD) method is used, in which the user can map the geometry of the front electrode in the form of a 2D and 3D image and measure the contact resistance and resistivity values at the metal-semiconductor junction. However, this method destroys the investigated material. By the second method, LBIC, the distribution of the short-circuit current is obtained without interfering with the tested material. This method also enables the presentation of the obtained result in a 2D and 3D graphic image form.

ii. Measuring station equipped with the Sherescan device, also designed by SunLab — The high-class Sherescan device enables measurement using a four-point probe. There are three measurement modes of the device available, namely

   (1) measurement mode — sheet resistance of the emitter determines the measurement of the emitter diffusion layer at one or more points, reproduction of measurement result(s) in graphical form (chart, map) or text (statistical analysis),
   (2) p/n-conductivity mode — enables a single-point measurement of the wafer to recognize its conductivity type,
   (3) mode for measuring the resistance and contact resistivity of the photovoltaic cell.

   The first two mentioned approaches (i)–(ii) were used in this work.

iii. Station for measuring the I–U characteristics SS I–V CT-02 equipped with the SS150AAA solar radiation simulator from Photo Emission Tech — Three series of solar cells were investigated at this station. The measurement of I–V curves is performed in a classic "four probe" system (so-called Kelvin probe system), which meets the requirements of the European standard IEC 60904-1. Under precisely defined conditions of a specific radiation spectrum and temperature, the I–U characteristics were measured with the commonly used standard, the so-called STC (Standard Test Condition). The software included in the station made it possible to determine the following solar cell parameters: photovoltaic conversion efficiency (E_{ff}), short circuit current (I_{sc}), open circuit voltage (U_{oc}), voltage at the point of maximum power of the solar cell (U_m), current at the point of maximum power of the solar cell (I_m), fill factor (FF), maximum achievable power (P_m).

Microstructural investigations of the solar cells were performed using the Zeiss Supra 35 scanning electron microscope (SEM) using secondary electron detection with an accelerating voltage in the range of 5–20 kV. Microchemical analysis of chosen parts of the solar cells was performed using a scanning electron microscope equipped with an energy dispersive X-ray (EDS) spectrometer.

4. Discussion of the research results

The measurement results obtained using the Corescan device are presented in Table I and Figs. 4 and 5. Analyzing the results from Table I, it was found that for the three series, the value of R_c ranges from 1.2 to 5.3 Ω cm, the resistivity ranges from 14 to 190 mΩ cm^2, and the measured voltage ranges from 3.9 to 17.6 mV. The lowest resistance and resistivity values were obtained for solar cells from the first series. It can be concluded that the best resistance and resistivity result was obtained for the solar cell no. 1 (R_c = 1.2 Ω cm, ρ_c = 14 mΩ cm^2). Based on the results presented graphically in Fig. 1, significant defects in the tested solar cells were observed using the Corescan device.

Figure 2 shows the results of the measurement of the short-circuit current distribution in solar cells using the Corescan device using the LBIC method. Based on the obtained test results, it was found that the graphical presentation of the front topography of the photovoltaic cells is almost identical. Slight differences in the short-circuit current distribution can be attributed to the areas with a very reduced carrier lifetime (Table II). In the case of the short-circuit current distribution on the surface of all solar cells, it was found to be more uniform and ranged from 67.1 to 69.1 mA/cm^2.

To estimate the diffusion layer of the solar cell emitter, the metrological capabilities of the station equipped with the Sherescan device were used. As a result of the measurement, the sheet resistance value was obtained in text form: average 46.2 Ω/□, standard deviation 1.4 Ω/□, median 45.3 Ω/□, maximum 48.2 Ω/□, minimum 45.1 Ω/□, and the graph (Fig. 6).

TABLE I

Resistance and resistivity parameters of selected solar cells.

Solar cell series no.	Solar cell no.	U [mV]	R_c [Ω cm]	ρ_c [mΩ cm^2]
I	1	3.9	1.2	14
	2	6.8	2.1	25
	3	4.9	1.8	18
II	4	17.6	5.3	63
	5	7.8	2.3	28
	6	10.7	3.2	39
II	7	13.2	4.0	47
	8	15.6	4.7	56
	9	12.7	3.8	190

TABLE II

Results of short-circuit current measurement on the surface of the investigated samples.

Solar cell series no.	Solar cell no.	I_{sc} [mA cm^2]
I	1	67.1
	2	67.1
	3	68.6
II	4	66.4
	5	69.6
	6	64.9
II	7	69.1
	8	69.1
	9	69.1

To identify the type of p/n conductivity of the tested solar cells, an example measurement was performed using the Sherescan device. As a result of the measurement, the conductivity type n of the solar cell was obtained, which means that an admixture of phosphorus was probably used (Fig. 7b).

Table III contains the calculated values of electrical parameters from additional software installed on the computer included in the I–V measurement station. The tested solar cells are characterized by short-circuit current (I_{sc}) in the range of 3.7–8.2 A, and an open circuit voltage (U_{oc}) in the range from 3.5 to 6.3 V (Table III). The next determined parameter, P_m, based on the characteristics, is the coordinate of the cell's operating point at maximum power for I_m and U_m. The values of P_m vary from 1.5 to 2.6 W in the I_m range of 3.5–6.3 A, and the fill factor FF varies from 0.4 to 0.8, while the processing efficiency E_{ff} ranges from 6.3–17.9% (Table III). In the case of series I, the highest value of photovoltaic conversion efficiency equal to 17.90% was obtained, while in the other two series, similar values differed by more than 1%, not exceeding 11%.

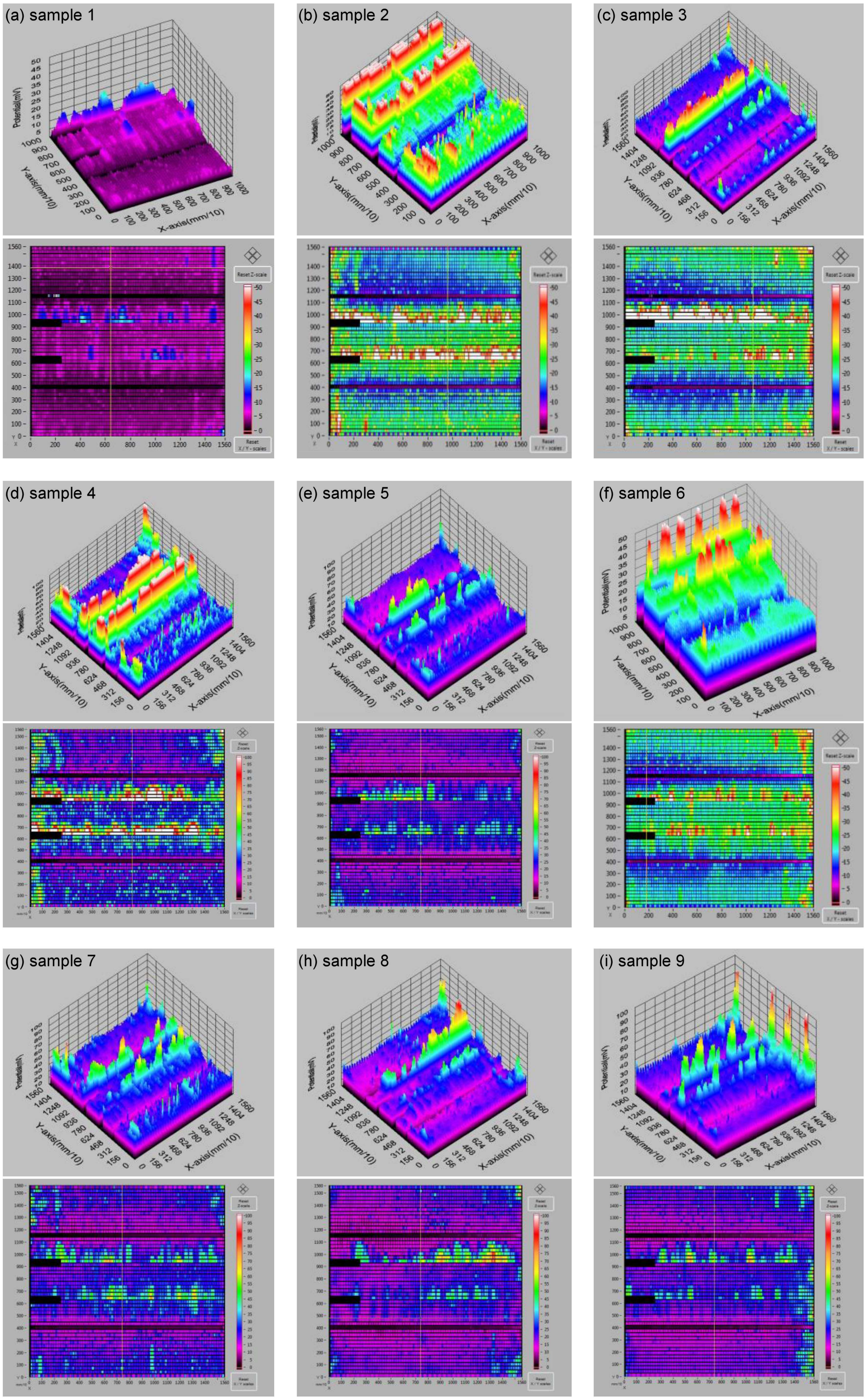

Fig. 4. Original measurement printout of the resistance distribution in the form of a 3D and 2D images for 9 solar cells.

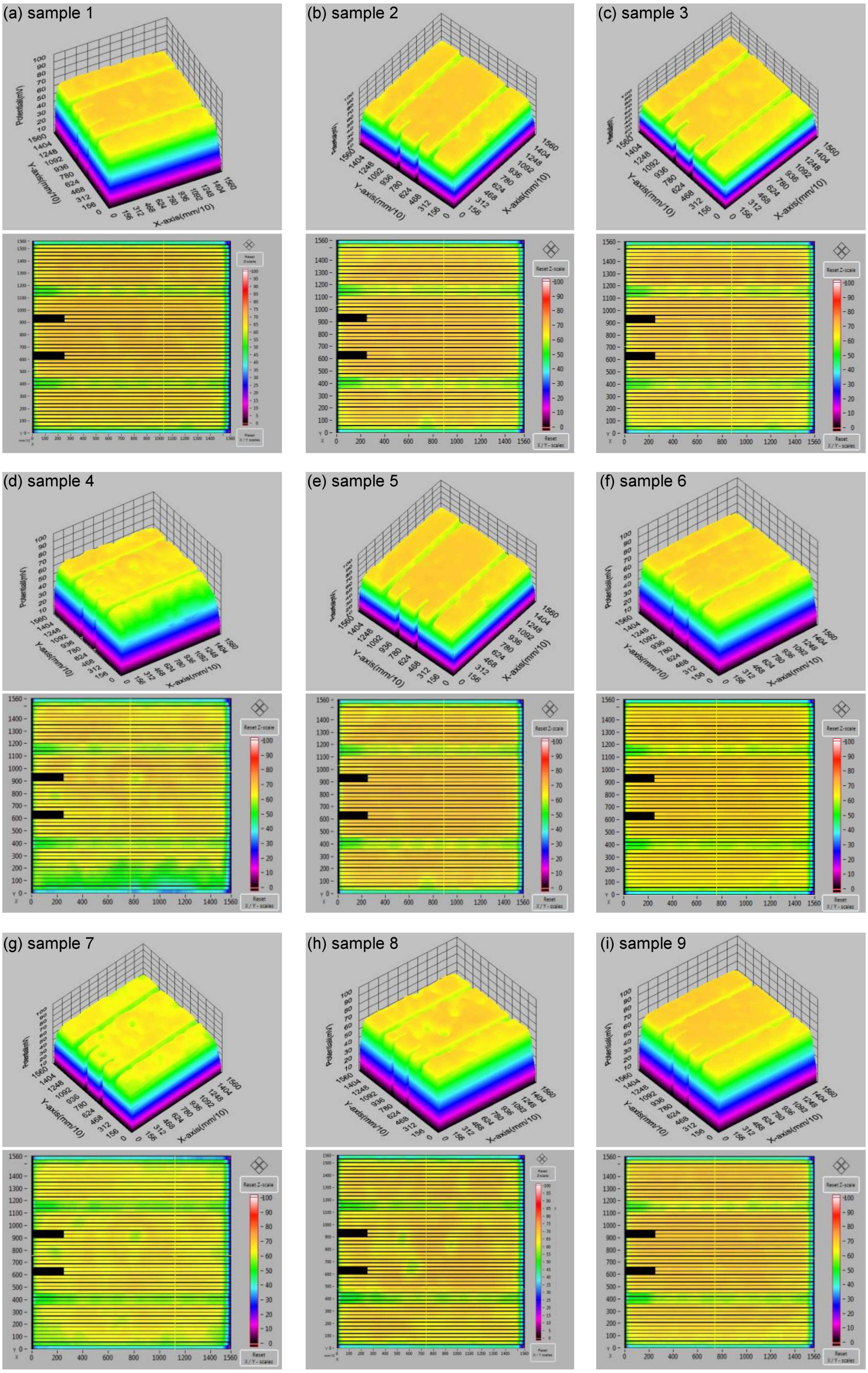

Fig. 5. Original printout of the measurement of the short-circuit current distribution on the surface of all solar cells in the form of a 3D and 2D image.

TABLE III

Electrical parameters of solar cells.

Solar cell series no.	Solar cell no.	Parameters						
		I_{sc} [mA]	V_{oc} [mV]	I_m [mA]	V_m [mV]	P_m [mW]	FF	E_{ff} [%]
I	1	3701.0	632.6	3534.1	517.1	1827.4	0.779	17.90
	2	7920.8	612.0	5260.9	393.5	2070.4	0.427	8.71
	3	8050.4	612.9	5627.7	391.4	2202.4	0.446	9.27
II	4	6423.7	603.0	3915.8	381.3	1492.9	0.385	6.28
	5	8012.9	609.5	5915.1	400.1	2366.3	0.485	9.98
	6	8166.2	612.7	6341.7	410.5	2603.2	0.520	10.98
II	7	7995.5	605.6	5563.8	392.7	2184.9	0.451	9.20
	8	7995.0	606.2	5828.2	399.0	2325.4	0.480	9.80
	9	7843.4	612.7	5403.1	402.9	2176.7	0.453	9.18

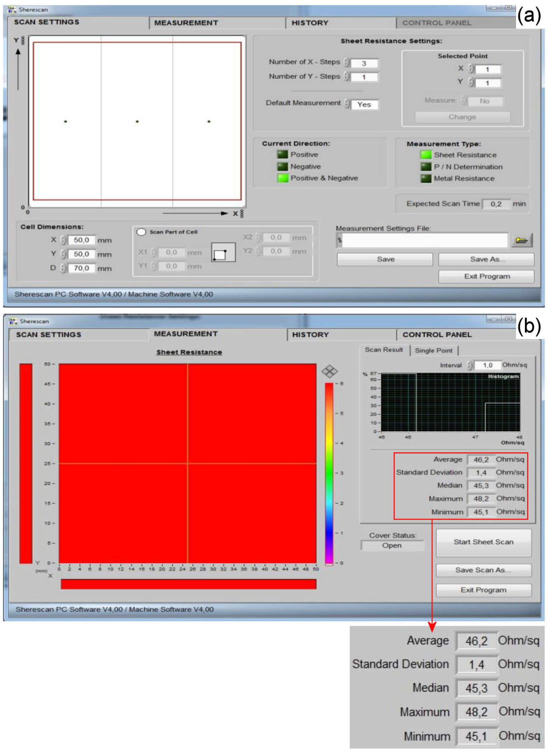

Fig. 6. View of the (a) scanning settings tab and (b) sheet resistance measurement tab.

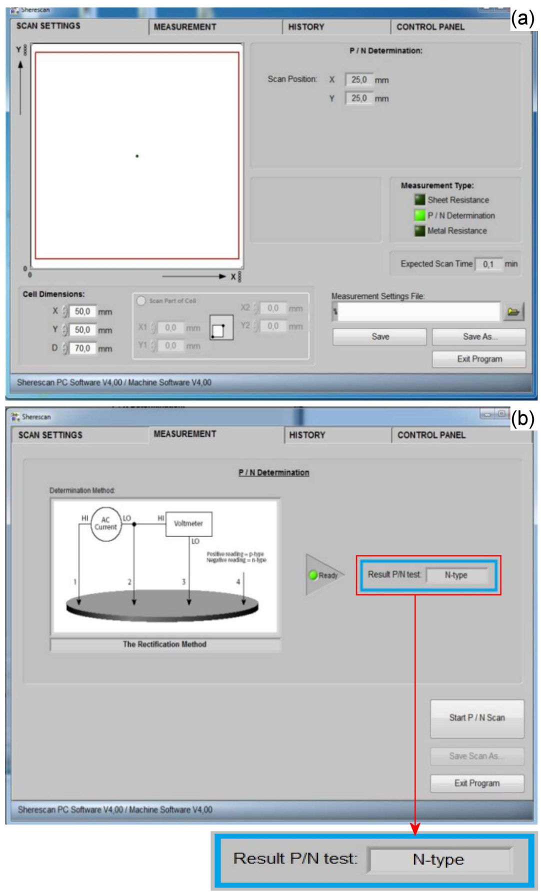

Fig. 7. Measurement of the recognition of the p/n conductivity type of a solar cell: (a) view of the scanning settings tab, (b) view of the measurement tab along with the obtained result.

Some conclusions were formulated in Table III presented in this article. During the investigations, for 9 solar cells, four (nos. 2, 7, 8, 9) and three (nos. 3, 5, 6) solar cells with similar I_{sc} and U_{oc} parameters were obtained.

It is common knowledge that a cell with high processing efficiency should be characterized by high values of short-circuit current I_{sc} and open circuit voltage U_{oc}, as well as a high value of fill factor FF. However, in the case of the I-series cell, no. 1 has the highest efficiency. The lowest short-circuit current value I_{sc} = 3701.0 mA can be found, which may result from some defect in the manufacturing operation of this solar cell. Analyzing the results obtained, it can be concluded that from the three series, two cells were obtained with the lowest and highest values of efficiency E_{ff}. The rest of the cells were in a similar range of values, i.e., from 6 to 11% (Fig. 8).

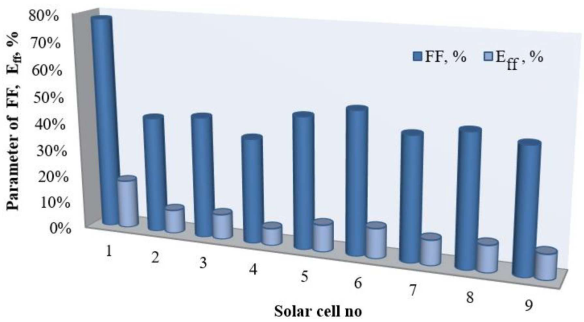

Fig. 8. Comparison of photovoltaic cells in terms of FF and E_{ff}.

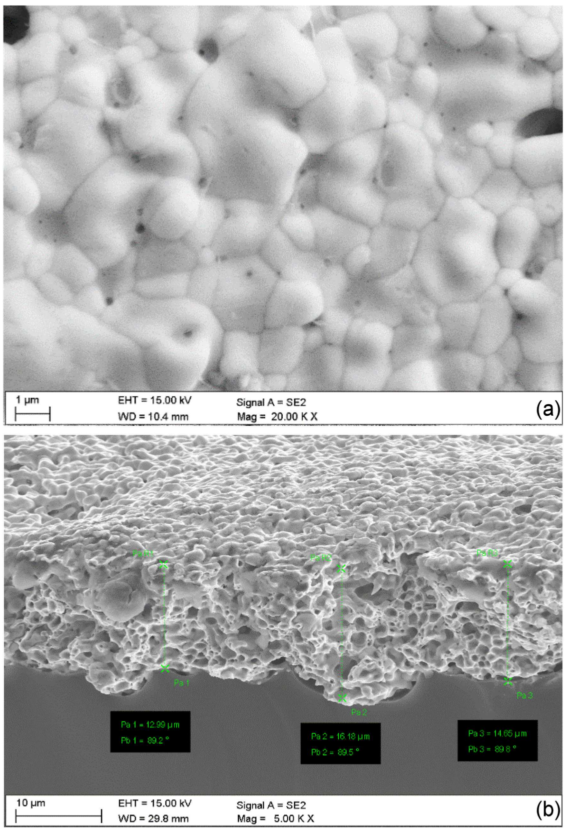

Fig. 9. Topography (a) and cross-section (b) of the front electrode (collecting path) of the chosen sample (SEM).

Figure 9 shows the results of the microstructural investigations of the front metallisation of the solar cell obtained using scanning electron microscope.

Topography observations show that the morphology of the deposited front electrode exhibits a porous structure. The size of individual pores ranges from a few to a dozen micrometers (Fig. 9a). Based on the fractographic investigations, it was found that the front electrodes manufactured from the commercial paste demonstrated a porous and irregular connection without delaminations (Fig. 9b).

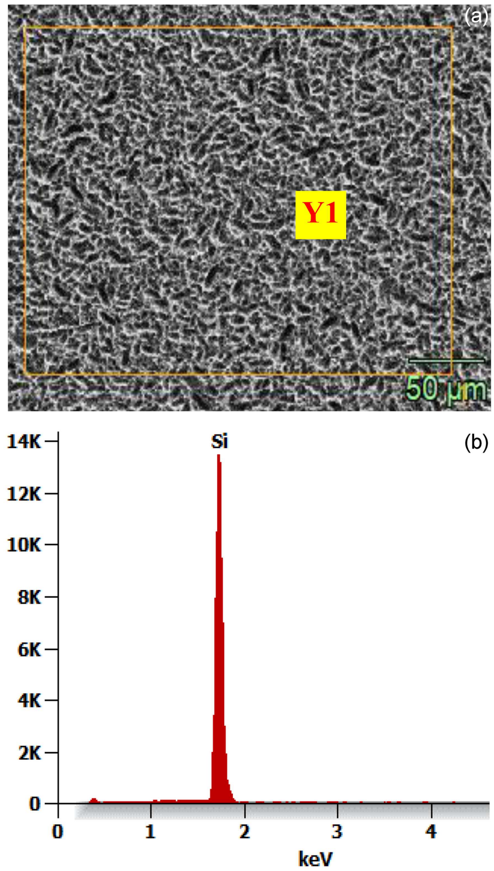

Fig. 10. (a) Si topography of sample no. 6 and (b) EDS microanalysis from the Y1 area.

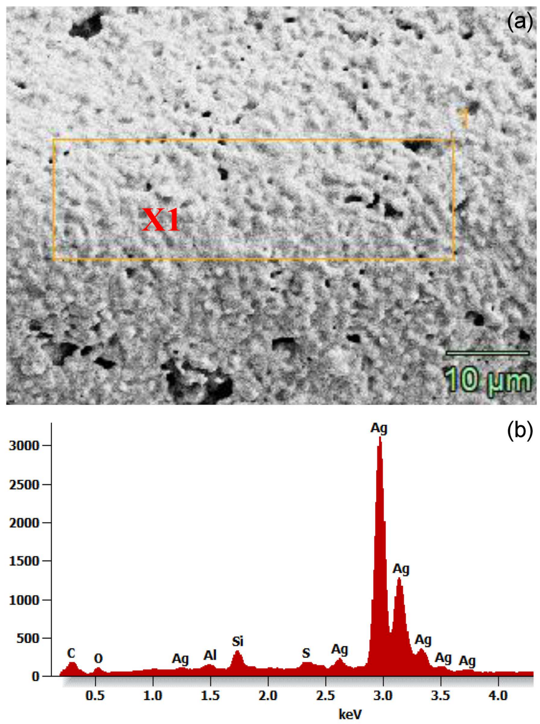

Fig. 11. (a) Front electrode topography of sample no. 6 and (b) EDS microanalysis from the X1 area.

Microscopic observations along with chemical composition analysis confirm the presence of elements suitable for the substrate (element Si) (Fig. 10b) and front electrode (mainly Ag element) of solar cells (Fig. 11b).

5. Conclusions

After conducting the research, the following conclusions were drawn:

i. Based on the results of solar cells tests obtained using a measurement station equipped with the Corescan device, significant defects in the tested material were found (Fig. 1). I-series solar cells had comparable uniform contact resistance. In the case of series III, solar cell no. 9 was characterized by the highest resistivity value.

ii. Based on the results of solar cells tests obtained using a measurement station equipped with the Corescan device, it was found that all samples were characterized by uniform short-circuit current flow (Fig. 2).

iii. Using the Sherescan station, information was obtained on the sheet resistance of the emitter diffusion layer and the type of silicon used for testing was identified.

iv. Analysis of the electrical parameters of solar cells manufactured in industrial conditions determined using a stand for measuring the I–U characteristics showed that their conversion efficiency is in the range of 9 to 11%. One solar cell had an efficiency of $\approx$ 18%. One can only assume that the cells were made in a different technological processes.

v. Both the morphology and the cross-sectional structure of the front electrode of the solar cell are porous and irregular.

vi. Analysis of the chemical composition confirmed the presence of elements suitable for the areas of the silicon solar cell and the front electrode.

Solar cell diagnostics are the key element in ensuring their optimal performance. Thanks to modern technologies such as thermal inspection, data analysis using artificial intelligence, and electrical and optical, as well as macro- and microstructural analysis, it is possible to effectively detect problems and solve them quickly. In the context of the growing importance of renewable energy sources, investments in diagnostics are a step towards sustainable development and energy efficiency. The article presents an example of the analysis of electrical properties on ready-made solar cells. However, often applied test stands can already be used at earlier stages of the technological process of the production. Diagnostics serve to optimize this process and may concern many aspects, but one of them is the analysis of electrical properties.

References

[1] EUR-Lex, An Energy Policy for Europe, 2007 (access: Sep. 2024).

[2] EUR-Lex, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (OJ EU L328/82), 2018.

[3] A. Goetzberger, J. Knobloch, B. Voss, *Crystalline Silicon Solar Cells*, John Wiley & Sons, Chichester (UK) 1998.

[4] K.W. Böer, *Survey of Semiconductor Physics*, Van Nostrand Reinhold, New York 1992.

[5] M.A. Green, in: *7th E.C. Photovoltaic Solar Energy Conf.*, Springer, Dordrecht 1987, p. 681.

[6] M.A. Green, S.R. Wenham, J. Zhao, in: *Proc. of the 11th European Photovoltaic Solar Energy Conf., Montreux 1992*, 1993, p. 41.

[7] M.A. Green, K. Emery, D.L. King, S. Igari, W. Warta, *Prog. Photovolt.* **12**, 55 (2004).

[8] Z.M. Jarzębski, *Energia Słoneczna: Konwersja Fotowoltaiczna*, PWN, Warsaw 1990 (in Polish).

[9] E. Klugmann-Radziemska, *Fotowoltaika w Teorii i Praktyce*, BTC, Legionowo 2010 (in Polish).

[10] A. Chmielewski, J. Kupecki, Ł. Szabłowski, K.J. Fijałkowski, J. Zawieska, K. Bogdziński, O. Kulik, T. Adamczewski, Available and Future Forms of Energy Storage, WWF, Warsaw 2020.

[11] Neo Energy Group Czy magazynowanie energii się opłaca? Najważniejsze korzyści (access: Nov. 2023, in Polish).

[12] D. Głuchy, *Poznan Univ. Technol. Acad. J. Electr. Eng.* **87**, 191 (2016) (in Polish).

[13] Hewalex, Typowe wady paneli fotowoltaicznych niskiej jakości (access: Sep. 2024, in Polish).

[14] PCC, Działanie oraz wady i zalety fotowoltaiki (access: Sep. 2024, in Polish).

[15] Gmina z Energią, Rodzaje uszkodzeń i wady paneli fotowoltaicznych cześć I (access: Sep. 2024, in Polish).

[16] K. Kuczyński, G. Dymny, Elektro Info, Zastosowanie kamer termowizyjnych do inspekcji instalacji PV, 2021 (access: Sep. 2024, in Polish).

[17] M.T. Sarniak, *Podstawy Fotowoltaiki*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2008 (in Polish).

[18] SBF, Fotowoltaiczny Dekalog Dobrych Praktyk (access: Nov. 2024, in Polish).

[19] T. Żdanowicz, *Materials XII School of Optoelectronics, Kazimierz Dolny*, 1997, p. 159.

[20] SOEN, Konserwacja paneli słonecznych: Wskazówki i najlepsze praktyki (access: Sep. 2024, in Polish).

[21] Czyste Panele, 5 korzyści wynikających z przeprowadzania przeglądów termowizyjnych instalacji fotowoltaicznych przy pomocy dronów (access: Sep. 2024, in Polish).