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APPLICATION EXAMPLES FOR THE DIFFERENT MEASUREMENT MODES OF ELECTRICAL PROPERTIES OF THE SOLAR CELLS

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The aim of the paper was to apply the newly developed instruments 'Corescan' and 'Sherescan' in order to measure the essential parameters of producing solar cells in comparison with the standard techniques. The standard technique named the Transmission Line Method (TLM) is one way to monitor contacting process to measure contact resistance locally between the substrate and metallization. Nowadays, contact resistance is measured over the whole photovoltaic cell using Corescanner instrument. The Sherescan device in comparison with standard devices gives a possibility to measure the sheet resistance of the emitter of silicon wafers and determine of both P/N recognition and metal resistance. The Screen Printing (SP) method is the most widely used contact formation technique for commercial silicon solar cells. The contact resistance of manufactured front metallization depends of both the paste composition and co-firing conditions. Screen printed front side metallization and next to co-fired in the infrared conveyor furnace was carried out at various temperature from 770°C to 920°C. The silver paste used in the present paper is commercial. The investigations were carried out on monocrystalline silicon wafers. The topography of co-fired in the infrared belt furnace front metallization was investigated using the atomic force microscope and scanning electron microscope (SEM). There were researched also cross sections of front contacts using SEM microscope. Front contacts of the solar cells were formed on non-textured silicon surface with coated antireflection layer. On one hand, based on electrical properties investigations using Sherescan instrument it was obtained the knowledge of the emitter sheet resistance across the surface of a wafer, what is essential in optimizing the emitter diffusion process. On the other hand, it was found using Corescan instrument that the higher temperature apparently results in a strongly decreased contact resistance.

Keywords: Electrical Properties, Solar cells, Screen printing, Contact resistance

Celem pracy było zastosowanie niedawno opracowanych urządzeń „Corescan" i „Sherescan" do zmierzenia zasadniczych parametrów wytwarzanych ogniw słonecznych w porównani z standardowymi technikami. Standardowa technika nazywana metodą linii transmisyjnych TLM (ang. Transmission Line Method) jest jednym ze sposobów monitorowania procesu pomiaru rezystancji strefy połączenia elektrody z podłożem. Obecnie, rezystancja kontaktu ogniwa słonecznego jest mierzona przy użyciu urządzenia Corescan. Urządzenie Sherescan w porównaniu ze standardowymi urządzeniami daje możliwość pomiaru rezystancji powierzchniowej warstwy dyfuzyjnej emitera płytek krzemowych i rozpoznania typu przewodności P/N i rezystancji kontaktu. Obecnie większość krzemowych ogniw fotowoltaicznych produkowanych na skalę przemysłową wytwarza się z zastosowaniem metody sitodruku do nanoszenia przedniej i tylnej metalizacji. Rezystancja kontaktu wytworzonej przedniej metalizacji zależy zarówno od składu pasty i warunków wypalania. Elektrodę przednią nadrukowano metodą sitodruku, a następnie wypalano w piecu taśmowym w zakresie temperatury od 770°C do 920°C. W niniejszej pracy zastosowano komercyjną pastę srebrną. Badania wykonano na płytkach krzemowych monokrystalicznych. Topografię powierzchni wypalanej w piecu taśmowym przedniej elektrody wykonano stosując mikroskop sił atomowych i skaningowy mikroskop elektronowy. Zbadano również przekroje poprzeczne przednich elektrod stosując skaningowy mikroskop elektronowy. Elektrody przednie ogniw słonecznych wytworzono na powierzchni krzemowej nieteksturowanej z naniesioną warstwą antyrefleksyjną. Na podstawie uzyskanych badań własności elektrycznych za pomocą urządzenia Sherescan stwierdzono, że w zakresie temperatury od 770°C do 920°C, rezystancja właściwa kontaktu mieści się w zakresie 0,43÷1,01 μ $\Omega/\square$ i rezystancja warstwowa kontaktu mieści się w zakresie 0,28÷0,67 m$\Omega/\square$ krzemowego ogniwa fotowoltaicznego. W wyniku badań własności elektrycznych wykonanych z wykorzystaniem urządzenia Corescan uzyskano szczegółową mapę powierzchni oporu styku pomiędzy emiterem a warstwą metalizacji ogniw słonecznych.

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1. Introduction

In the crystalline silicon solar cell technology one of the current trends is to reach highest efficiency on the wafers of minimized thickness. The thickness must meet the limit of approximately 200 μm caused by the difference of thermal expansion coefficients of Si and Al, which is used for a back contact. To reach optimum solar cell efficiencies, it is necessary also to reduce resistance losses to a minimum. The resistance loss, which is subdivided in series resistance and parallel resistance losses is one type of loss. It is very important to design properly both the size and shape of front electrode for the sake of mineralization of this loss. For approximately 90% of solar cells produced in industry, metallization is applied by screen printing of metal paste, followed by electrical and mechanical contact formation performed by co-firing in high temperature a belt furnace [8-15].

Important parameters determining the quality of the contact formation are e.g. paste composition or metal powder from which the paths are made, as well as manufacturing conditions. To reduce the contact resistance, it is important to be able to measure it. One way is to measure it using the Transmission Line Method (TLM), which nowadays it is generally known. TLM in comparison with the Corescan is slow and it is not able to give information as a function of position. To summarize, the Corescan does not have these limitations. Corescan makes possible to carry out the measuring onto the following ways [1-6]:

1. Corescan: Map contact resistance & finger resistance and interruptions of front side metallization in order to optimize & diagnose processes and/or pastes.
2. Shunt scan: Locate shunts on cells in order to find out about their nature.
3. Voc scan: Voc distribution in order to find locations of e.g. increased recombination (on cells without front side).
4. LBIC scan: Current distribution in order to locate regions with lower bulk lifetime, optimise gettering and hydrogen passivation.
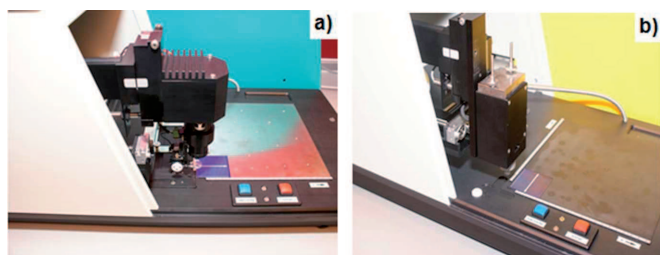

Fig. 1. Picture of instruments: a) Corescan, b) Sherescan

With the Corescan instrument (Fig. 1a), the contact resistance can be locally measured, and a complete scan for a 5 cm×5 cm solar cell depends on parameters (e.g. time) set up during a process.

The Sherescan instrument (Fig. 1b) uses a four probe measuring method. The measurements mode are the following [1]:

1. P/N type recognition, it means a single point measurement in order to recognize P or N type of the semiconductor material;

2. Sheet resistance, it makes possible for detailed mapping and single measurement of sheet resistance of emitters;
3. Metal resistance, the determination of specific resistivity of metal metallization on a solar cell, e.g. the resistivity of the busbar.

2. Experimental procedure

The investigations were done on wafers (100) from monocrystalline silicon produced by Deutsche Solar (Germany) about the area of 25 cm^2. Table 1 is presented the basic parameters of Si wafers. The wafers with thickness ~230 μm were applied in co-firing in the furnace.

TABLE 1

Testing material

The basic parameters of silicon	
Type	p
Doped	boron
Thickness	200±30 μm
Area	5 cm×5 cm
Resistivity	1÷3 Ω·cm

Front side metallization and connecting back contacts were printed using PV 145 and PV 124 paste produced by Du Pont company. Back side metallization was printed using CN53-101 Al conductor paste produced by Ferro company.

Technology of producing solar cells was performed in the Institute of Metallurgy and Materials Science in Krakow (Poland). The process steps for manufacturing solar cells included: chemical etching, p-n junction formation, parasitic junction formation, surface passivation of solar cell (SiO$_2$), antireflection coating deposition (TiO$_x$), screen printing front and back contacts and next to co-firing them in the conveyor IR furnace.

These solar cell were manufactured to demonstrate usefulness of silver paste and to evaluate the contact resistance of the silver electrode-silicon junction. In order to obtain the smallest resistance value of the connection zone electrode with silicon substrate of solar cell and also uniform structure without pores, a series for solar cells were prepared by co-firing in the furnace (Tab. 2). The conveyor IR furnace was equipped with tungsten filament lamps, heating both the top and bottom of the conveyor. The following investigations were performed in this paper:

- The topography of both surface and cross section of front contacts using scanning electron microscope (SEM), confocal laser scanning microscope 5 (CLSM).
- Electrical properties of solar cells with front metallization made conventionally on computerized Solar – Lab positioning table, consisting in measurement of I-V curves of the photovoltaic solar cells.
- Electrical properties of solar cells, with front metallization made conventionally on Corescan and Sherescan instruments produced by SunLab BV a daughter company of ECN Solar Energy research Centre of the Netherlands. The Corescan instrument was apply to map the contact

resistance of the front side metallization, locate shunts on solar cells and find out about their nature, find the locations of increased recombination (on research cells without front side metallization), find the regions on a solar cell with lower bulk lifetime. The Sherescan instrument was apply to recognize P/N type of Si wafer and metal conductivity, as well sheet resistance of the Si wafer after diffusion process.

TABLE 2

Conditions of co-firing in the furnace silicon solar cells (the thickness of electrode: 15 μm)

Series	Paste symbol	Temperature, °C		
		Zone I	Zone II	Zone III
1	PV 145	530	570	770
				830
				920

3. Results and discussion

Based on metallographic observations in the scanning electron microscopy, it was found that front metallization obtained from silver PV 145 paste and co-fired in the furnace selective laser sintered show shows a porous structure (Fig. 2). Moreover, obtained electrodes demonstrate structure with different density grades depending on co-firing temperature. Front electrodes solar cells obtained at the lowest temperature of co-firing (770°C) show a more porous structure rather than contacts sintered at the highest temperature (920°C), which show very homogenous structure obtained in a consequence of contact pitting and their melting (Fig. 3).
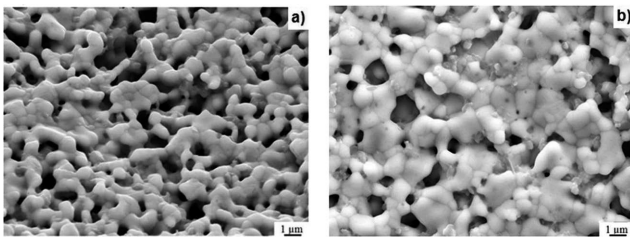

Fig. 2. SEM images of front contact layer co-fired in the furnace at the temperature: a) 770°C, b) 920°C from PV 145 paste on Si substrate without texture and with antireflection layer
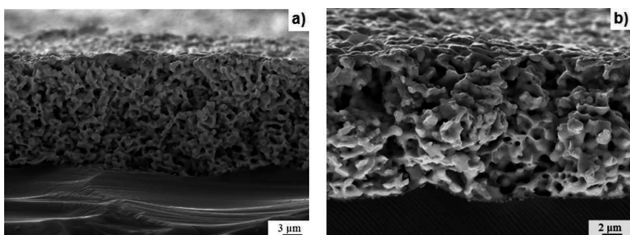

Fig. 3. SEM fracture images of front contact layer co-fired in the furnace at the temperature: a) 770°C, b) 920°C from PV 145 paste on Si substrate without texture and with antireflection layer

The thickness of test electrodes was determined based on the measurement of profile height three dimensional surface topography in the confocal scanning microscope (Fig. 4).
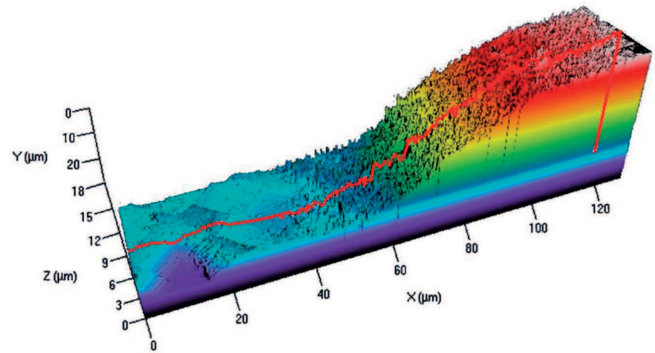

Fig. 4. Three-dimensional surface topography (CLSM) of the front electrode prepared from the PV 145 paste on a surface without texture and with antireflection layer co – fired in the furnace at 830°C temperature (example)

Based on both the metallographic and on the measurement of profile height three dimensional surface observations, it was found that the thickness testing front electrodes co-fired in the lowest temperature 770°C do not decrease or decreases the thickness is slight with relation to thickness of electrodes before their co-firing. As a result of investigations, the investigated testing front side contacts co-fired in the furnace show diverse thickness on cross-section in the range from 8 to 15 μm.

Electrical properties of solar cells, with front side metallization obtained from PV 145 paste, co-fired in the furnace in the temperature range from 770 to 920°C, determined from I-V curves let confirmed that their efficiency is equal to E_{ff} = 0.10÷13.38% and fill factor is equal to FF= 0.10÷0.65 (Tab. 3). In solar cells with the smallest efficiency the following reduced short circuit current value was obtained (I_{sc}) of 67.69 mA and open-circuit voltage (U_{oc}) of 202.70 mV (Tab. 4). It was found based on electrical properties that the surface morphology has a significant effect on value of conversion of the solar energy into electrical energy by solar cell.

Example scans on solar cells, in which front side metallization was screen printed and co-fired in the infrared at various temperature are given in this section in order to demonstrate the application of the Corescan for contact formation optimization. The temperature setting ranged from T+770°C to T+920°C. The Corescan results are given in Fig. 5. In the Table 3, maximum FF is reached at 920°C temperature. The degradation in FF for the other temperature settings is caused by increased contact resistance losses. One of observations is that it is possible to deduce from the contact resistance distribution whether a cell is co-fired correctly or under-fired, because this gives possibility for an easy optimization of the temperature setting. The higher temperature apparently results in a strongly decreased contact resistance (Fig. 5).

Electrical properties of silicon solar cells co-fired in furnace from PV 145 paste

Solar cell symbol	Co-firing temperature [°C]	Electrical parameters						
		U_{oc} [mV]	I_{sc} [mA]	I_m [mA]	U_m [mV]	P [mW]	FF	E_{ff} [%]
Photovoltaic solar cell without texture with coated antireflection layer								
A	770	202.70	67.69	6.41	208.20	1.34	0.101	0.10
B	830	564.23	344.53	169.88	305.28	51.86	0.267	2.07
C	920	590.93	866.76	740.32	451.76	334.45	0.653	13.38

I_{sc}– short circuit current of solar cell, I_m – a current in maximum power point of solar cell, U_m – a voltage in maximum power point of solar cell, U_{oc} – open-circuit voltage of solar cell, FF – fill factor of solar cell, P – power of solar cell, E_{ff} – efficiency of solar cell

Electrical parameters of photovoltaic solar cells co-fired in the furnace from PV 145 paste assigned based on fitting I-V curve of chosen solar cells to the theoretical two diode model

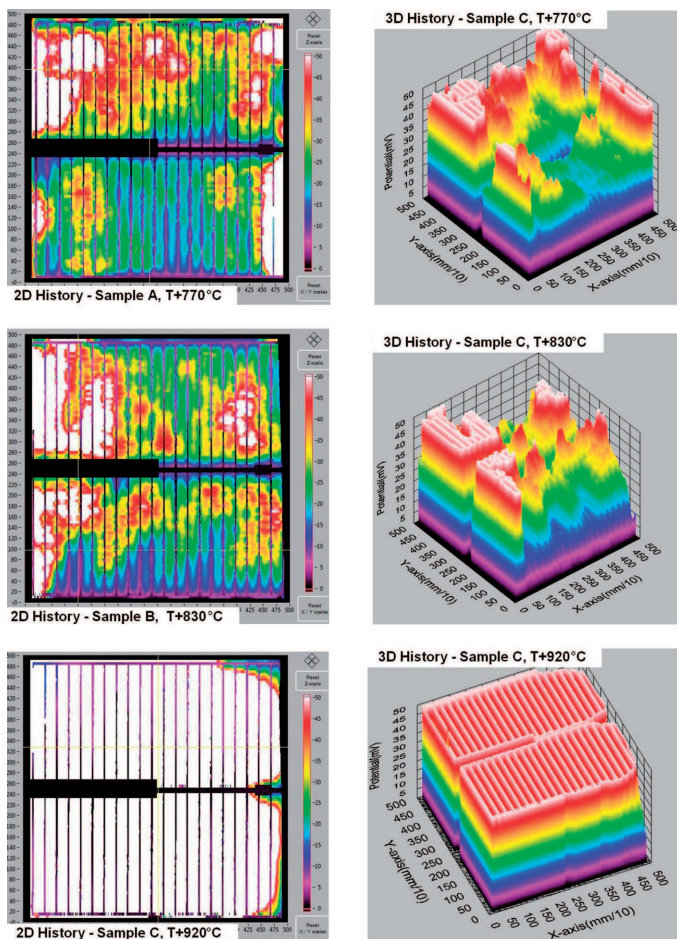| Solar cell symbol	Co-firing temperature [°C]	Electrical parameters							
		I_p [mA]	R_{sh} [Ω]	R_s [Ω]	I_{s1} [A]	I_{s2} [A]	A_1	A_2	ε [%]
Photovoltaic solar cell without texture with coated antireflection layer									
A	770	103.01	8.64	2.97	3.45e-7	1.47e-4	1	1.80	43.60
B	830	721.45	1.29	0.29	4.88e-11	4.60e-6	1	2.03	3.79
C	920	859.54	12.02	0.08	3.32e-11	4.90e-5	1	2.50	0.38

Fig. 5. Corescan potential mappings on cells co-fired at various temperature. Lighter areas have higher contact resistance

P/N type of silicon wafers were recognized using Sherescan instrument equipped with mode of measurement: P/N recognition (Fig. 6). As result of measurement was obtained p – type of silicon wafer (Fig. 6b). Figure 7 presents a typical cross mapping, which shows the sheet resistance values, with a high resistance area in the whole part. This way of mapping and representation, as used for semi-conductor applications, does enough for solar cell applications. As a result of measurement were obtained the following results: average: 47.6 Ω/□, standard deviation 1.1 Ω/□, median 47.5 Ω/□, max.49.0 Ω/□, min. 46.3 Ω/□.
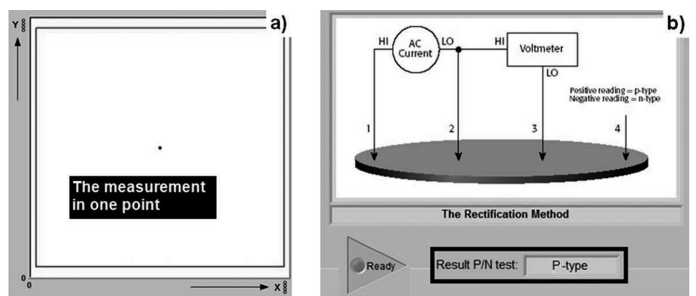

Fig. 6. Measurement of P/N determination on Si wafer (an example): a) a view of scan settings, b) a view of measurement result

Figure 8 presents the panel of the result of the metal resistance measurement. The data in the plot show the resistance across a silver busbar. From these data the sheet resistance, and also the specific resistivity of the metal were calculated (Tab. 5). The smallest metal resistance measurements were obtained for a C sample co-fired in the furnace in 920°C temperature.
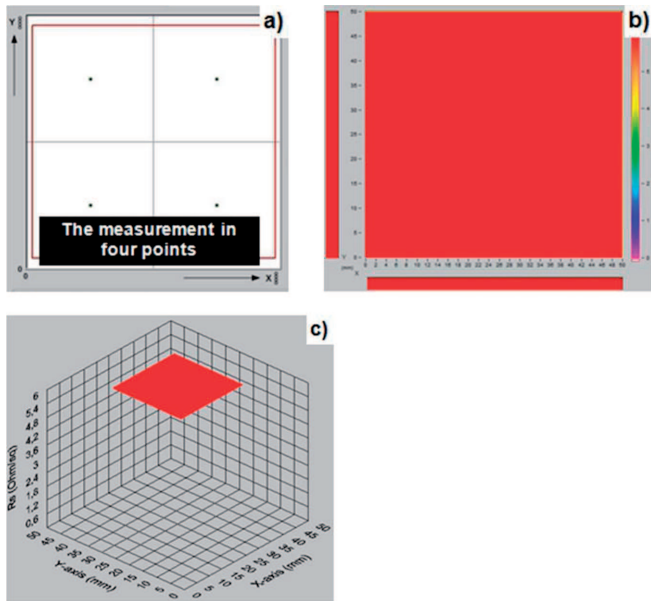
Fig. 7. Procedure measurement of the emitter sheet resistance across the surface of a single wafer (an example): a) a view of scan settings, b) a view of measurement result, c) a view of three-dimensional measurement
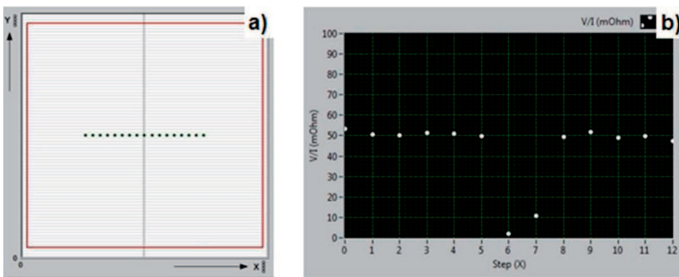

Fig. 8. Procedure measurement of specific resistivity of metal: a) a view of scan settings, b) a view of measurement results (example)

TABLE 5

The metal resistance measurements

Solar cell symbol	Co-firing temperature [°C]	Specific resistivity of metal	
		Sheet resistance of metal [mΩ/□]	Specific resistivity of metal [μ Ωcm]
A	770	0.674	1.011
B	830	0.390	0.586
C	920	0.280	0.430

4. Summary

On the basis of metallographic observation, it was found that the morphology a test electrode system deposited from paste PV 145 and co-fired in the furnace shows a porous structure, porosity grade depended on co-firing temperature. On the basis of electrical properties investigations using Sherescan instrument it was found that in the temperature range from 770°C to 920°C the specific resistivity of contact is equal

0.43÷1.01 $\mu\Omega/\square$ and the sheet resistance of metal contact is equal 0.28÷0.67 mΩ/□ onto non-textured substrate having coated antireflection layer of silicon solar cells. On the basis of electrical properties investigations using Corescan instrument it was found that the higher temperature apparently results in a strongly decreased contact resistance.

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