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The investigation of the properties of solar cells based on Kazakhstan silicon

The study of the properties of solar cells is a relevant topic since the development of solar energy corresponds to the global trend and the course of the Government of the Republic of Kazakhstan on the transition to a «green» economy. Various properties of solar cells such as resistivity and surface resistance, carrier lifetime, reflectivity, quantum efficiency, directly affect the efficiency of solar cells. This paper is devoted to obtaining and comprehensive study of solar cells manufactured on the basis of the Kazakhstani silicon of «solar» quality. The study applied: a method of microwave detected photoconductive decay (μ-PCD), four probe methods for measuring resistance, methods for spectrometric analysis of reflection, transmission and photoluminescence coefficients, scanning electron microscopy, and methods for analyzing current-voltage characteristics. The mastered methods of solar cells production are described. A modification of the standard Back Surface Field (BSF) cell line to the Passivated Emitter and Rear Cell (PERC) line has been proposed.

Keywords: photoelectric converters, solar cells, silicon, Al-BSF structure, PERC structure, solar energy.

Introduction

As it is known [1], the world population is projected to grow from 7.6 billion (2018) to 9.2 billion by 2040. In response to a burgeoning population global energy use is forecast to increase by 28 % [2]. But in recent decades, energy consumption per capita has increased tenfold. As a result, the active production of energy from traditional types of hydrocarbon fuels (oil, coal, gas) led to a reduction in their reserves and to environmental pollution at the same time. All this has led to the need to find alternative unconventional approaches to energy generation. These sources include the energy of the sun.

As part of the transition to the «green» economy, in 2010, Kazakhstan began to implement a project for the production of photovoltaic modules based on the Sarykol quartz deposit. A consortium of French enterprises led by the Commissariat for Atomic Energy and Alternative Energy Sources of France took part in the «solar» project. The base material silicon is produced by carbothermic technology at the enterprise of the «Metallurgical Combine KazSilicon» LLP in the Ushtobe city, the production of solar cells and the assembly of modules is carried out at the factories of the «Kazakhstan Solar Silicon» LLP and the «Astana Solar» LLP, in the cities of Ust-Kamenogorsk and Astana, respectively.

In this paper, the implemented technology for the production of solar cells at «Kazakhstan Solar Silicon» LLP is considered. However, the production technology of solar cells based on multicrystalline silicon is constantly evolving and continuously improving. So, the natural progress from the Al-BSF structure production technology is the PERC structure [3].

The purpose of this work is to study and analyze the properties of photoelectric converters. Based on the obtained results of a comprehensive study, we conclude that it is possible to modify the existing line in order to increase the efficiency of solar cells.

Materials and methods

The material for the study is solar grade multi crystalline silicon (SOG mc-Si) wafer, with a thickness of 180-200 microns. Silicon wafers passed all stages of technological operations, such as: texturing, emitter creation by phosphorus diffusion method, removal of phosphorosilicate glass, antireflection coating deposition, metallization (creating a contact grid and current collecting busbars), and firing. As a result of a series of physicochemical processes, solar cells were obtained.

The solution of hydrochloric and nitric acids (HCl / HNO_3) was used to texturize the silicon wafer surface, as a result of which wells were formed on the surface, regardless of the orientation of the crystals. For etching a layer of porous silicon, silicon wafers were treated in a solution of potassium hydroxide (KOH), and then with the purpose of etching metals – in a solution of hydrofluoric and hydrochloric acids (HF / HCl). The X-Rite SP62 spherical reflectometer was used to measure reflectivity. This system measures the spectrum of the light source incident on the surface and the spectrum of light reflected from the surface, then compares the measured spectra. An analysis of the surface morphology of silicon wafer before and after texturing was performed by scanning electron microscopy using a JSM-6390LV microscope.

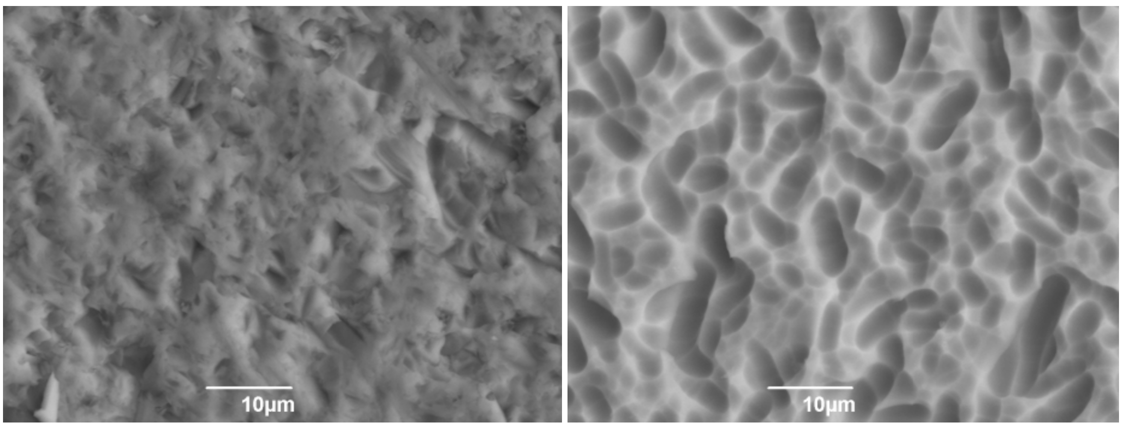
The emitter was formed using the diffusion method on Lydop equipment of Semco Engineering at the next stage. Phosphorus doping was carried out at a pressure slightly below atmospheric and at temperatures of 830–860 °C. The phosphorus oxychloride $POCl_3$ was used as a source of phosphorus, which is fed into the reactor along with nitrogen. The emitter, formed at a depth of 0.3-0.5 μm, has two functions: the formation of a p/n junction with the base and the transfer of electrons to metal contacts. For the analysis of the surface resistance of the formed emitter, CMT SR2000N device for measuring the surface and specific resistance by the 4-probe method was used. In order to evaluate the effect of gettering and measuring the lifetime of minority charge carriers, we used the method of measuring photoconductivity decay in the microwave range (μ-PCD) using the WT-2000 PVN Semilab measuring system at a laser wavelength of 904 nm.

Plasma-enhanced chemical vapor deposition (PECVD) was used for antireflection coating (ARC) depositing. The deposition of silicon nitride film was carried out in a vacuum chamber at a temperature of 350-450 °C in the presence of silane (SiH_4) and ammonia (NH_3). The thickness of the obtained antireflection coating, measured using Semilab LE-200PV ellipsometer by polarization-optical method, was 75 nm.

Metallic contacts and busbars were screen printed on Dubuit equipment. For the front side busbars and grids, silver-containing conductor paste with a specific resistance of less than 2 mΩ /sq and viscosity of 16-23 Pa*s was used, and for rear current-collecting busbars – silver paste with a resistance of 5 mΩ / sq and viscosity of 89 Pa*s. For the BSF creation, which plays the role of not only the rear solid contact but also a passivating layer, aluminium paste was used, with a resistance of 0.05 Ω /sq and a viscosity of 50 – 70 Pa*s.

Results and discussion

Figure 1 shows the obtained images of the silicon wafer surface before texturing (Fig. 1a), and after (Fig. 1b).



a) b)

Figure 1. Scanning electron microscope (SEM) image of the wafersurface: a) before texturing; b) after texturing

As Figure 1a shows, the surface of the source wafer is severely damaged. There is a huge number of cavities, microcracks and hills on it – this is the disturbed layer that was formed during the wafer production (cutting ingots into wafers). Such surface is simply destructive for solar cells due to the extremely high surface recombination rate. After texturing and etching, the wells formed on the surface of the wafer (Fig. 1b), which leads to a significant decrease in reflectivity (Fig. 2).

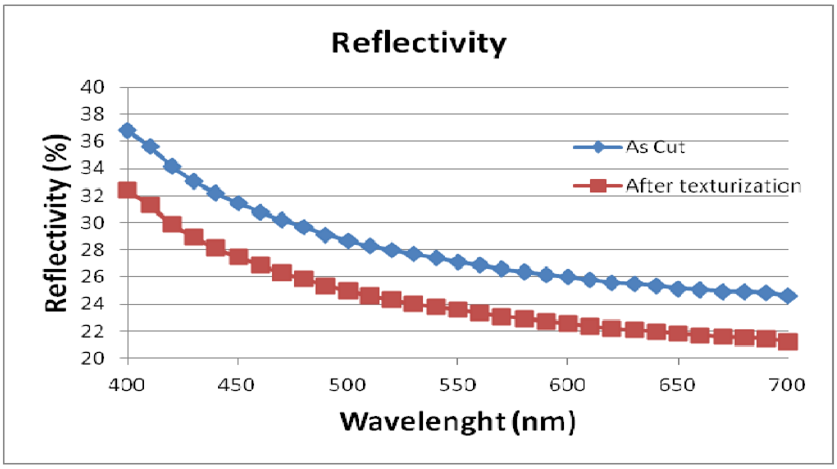


Figure 2. The reflectivity before and after texturing, obtained by spherical spectrometry on X-Rite SP62 reflectometer

CMT SR2000N device for measuring the sheet resistance and resistivity by the 4-probe method was used to determine the sheet resistance (Rsh).

The resistivity was determined by the formula [4]:

$$Rho = Rsh \bullet t, \tag{1}$$

where, Rho — resistivity, Ω*sm;

Rsh — sheet resistance Ω/sq;

t — silicon wafer thickness, sm.

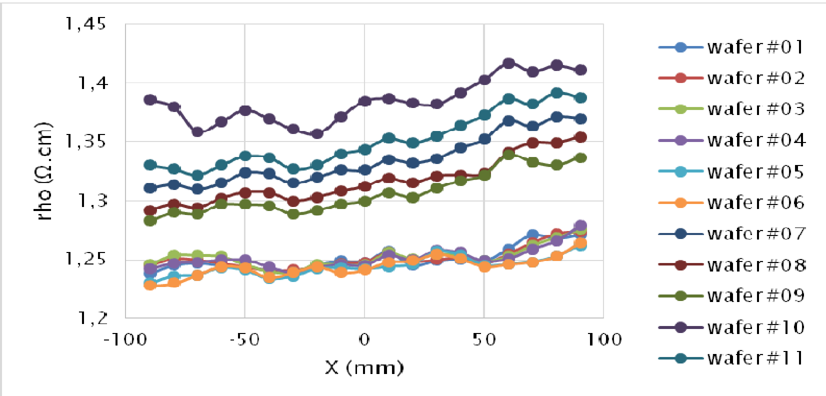


Figure 3. Silicon wafer resistivity obtained by the 4-probe method

Figure 3 shows the uneven distribution of resistivity across a sample of the wafer that can negatively affect the solar cell performance. The uniformity of the distribution of the average value of r_{ho} is 5.46 %.

A method for measuring the photoconductivity decay in the microwave range (μ-PCD) on the WT-2000 PVN measuring system was used to map the distribution of the lifetime of minority charge carriers (Fig. 4), and also their average values were obtained.

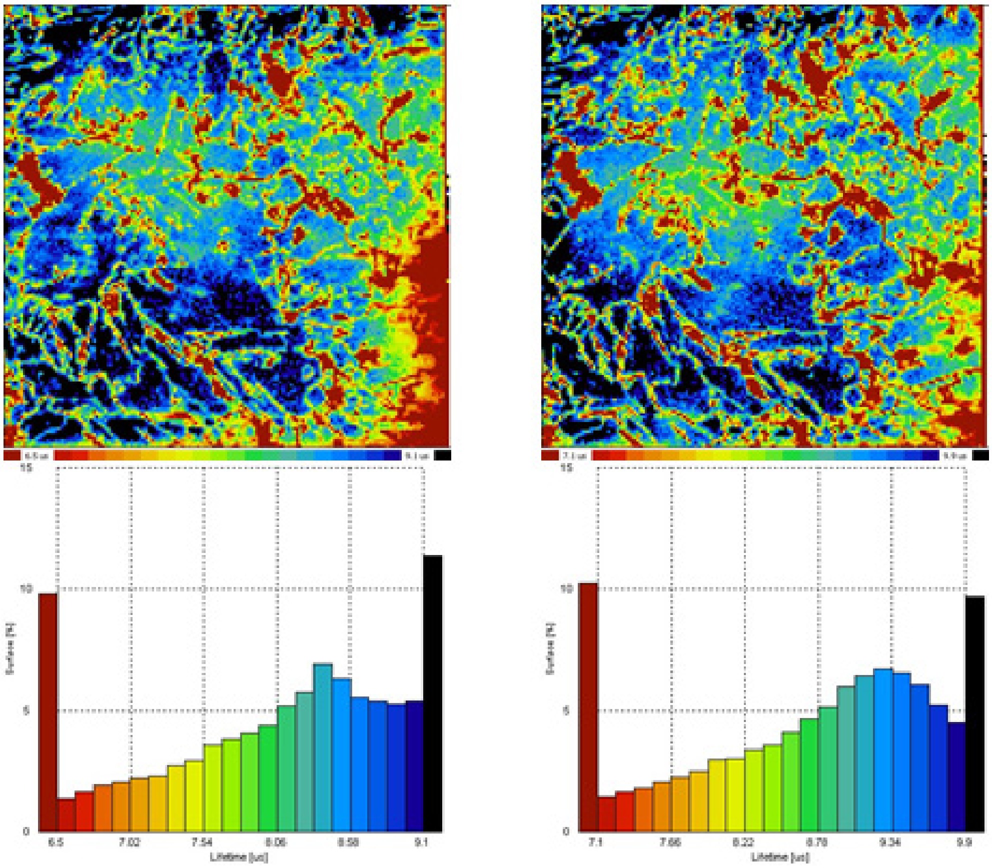


Figure 4. Maps of the lifetime of minority charge carriers distribution in wafer

The study showed that the lifetime of free charge carriers increased from 2 μs (before the diffusion process) to 11.6 μs (with a formed emitter after diffusion) with a uniformity coefficient of 1.5 %. As can be seen in Figure 4, the lifetime is distributed more evenly, with the exception of the boundary zones, where an accumulation of lattice defects and recombination zones formed during the crystallization process occurred.

It is known [5–8] that the surface of a multicrystalline silicon wafer is the maximum possible disorder in the symmetry of the crystal lattice, as a result of which the surface recombination of charge carriers increases. Surface recombination can greatly affect the short circuit current and the open-circuit voltage. Surface recombination has a particularly detrimental effect on the short-circuit current, since the front surface is also the region with the highest carrier generation in the solar cell. The reduction in high surface recombination is usually achieved by reducing the number of dangling bonds on the surface by passivation. In this work, the surface was passivated using non-stoichiometric films with a large amount of hydrogen (Si_xN_y: H) applied by the PECVD method. An ellipsometer Semilab LE 200PV was used to measure the thickness and refractive index of the films obtained. The refractive index was 2.05-2.06, and the thickness of the films obtained was in the range from 73 to 78 nm.

The study of the properties and parameters of silicon wafers and solar cells by the method of spectrometric analysis of photoluminescence on a Luminescence ImaGing System – Model LIS-R1 measuring system was conducted at the National Institute for Solar Energy of France, INES. Photoluminescent Imaging (PL-images) of silicon wafers (Fig. 5) and solar cells (Fig. 7) were obtained.

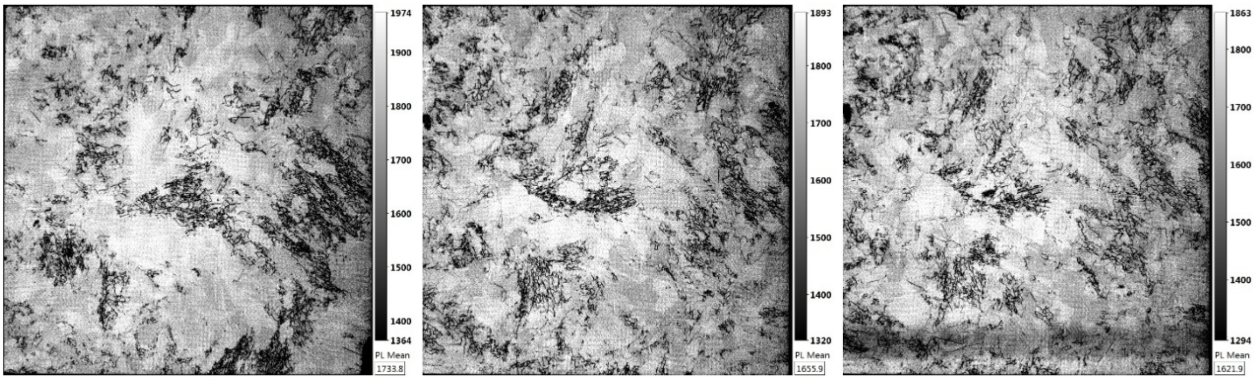


Figure 5. PL-images of wafer (samples 1, 7, 10) obtained on the Luminescence ImaGing System - Model LIS

The dark zones presented in the PL images of silicon wafers (Fig. 5) can be the sites of dislocation accumulations that occur during the crystallization of silicon ingots. These defects adversely affect the performance of solar cells.

The reflectivity is one of the main parameters affecting the efficiency of the finished solar cells. Figure 6 presents the results of measurements of the reflectivity of the samples under study by the method of spectrometric analysis of the reflection and transmission coefficients. For the analysis ready-made solar cells coated with anti-reflective coating were selected.

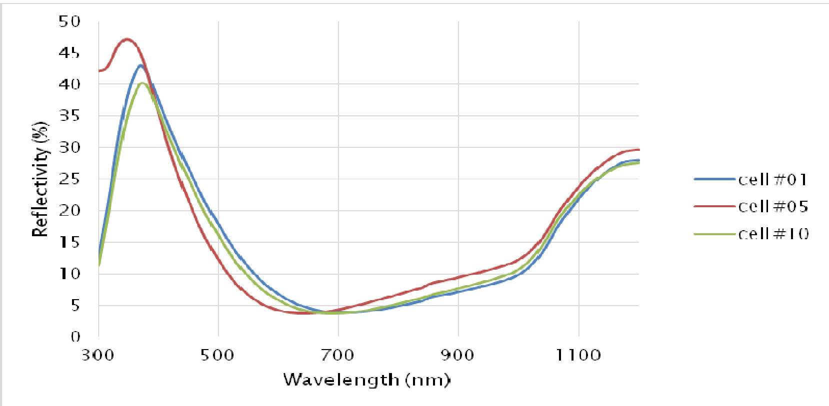


Figure 6. The reflectivity of solar cells at different wavelengths

The graph of the dependence of reflectivity on the wavelength of the incident radiation shows that the solar cells under study have the lowest reflectivity at 660-680 nm, which increases dramatically at a wavelength of more than 700 nm. This, of course, limits the possibility of charge separation in the spectrum and leads to a decrease in efficiency.

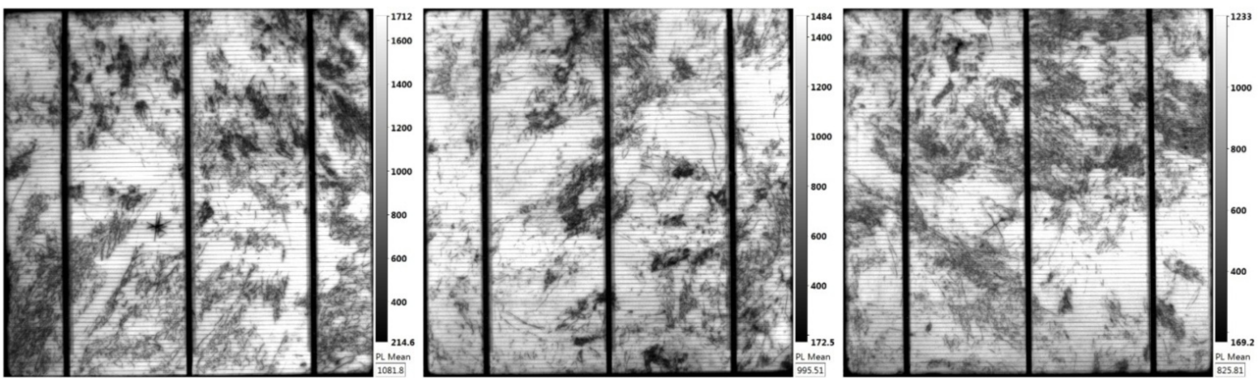


Figure 7. PL-images of solar cells (samples 1, 7, 10) obtained on the Luminescence ImaGing System - Model LIS-R1

Analysis of the obtained PL-images of solar cells (Fig. 7) proved the assumption that the dark zones are the result of the accumulation of defects arising in the process of crystallization and do not arise as a result of the physicochemical operations of the production of solar cells.

To measure the electrical parameters (short circuit current *Isc*, open circuit voltage *Uoc*, filling factor *FF*, maximum power *Pmpp*, efficiency *Eff*), the Solar simulator ORIEL Sol3A CLASS AAA was used. The measurement results are presented in Table.

Table

Electrical Parameters

Internal ID	Voc, [mV]	Isc [mA]	FF [%]	Pmpp [mW]	Eff [%]
cell #02	612,622	31,062	76,105	3788,435	15,567
cell #03	610,715	31,674	76,47	3863,883	15,877
cell #04	607,994	31,706	77,273	3869,516	15,9
cell #05	606,694	31,496	77,546	3846,173	15,804
cell #06	609,721	31,793	77,601	3882,786	15,955
cell #07	609,757	31,81	76,91	3877,285	15,932
cell #09	612,052	31,751	77,436	3881,803	15,951
cell #10	612,596	31,253	75,047	3809,801	15,655
average	**609,7397**	**31,5882**	**76,9674**	**3855,216**	**15,8415**

Thus, the studied samples of photovoltaic devices of Kazakhstan production showed efficiency in the range from 15.6 ÷ 15.9 %. As noted in [9], the average efficiency of mc-Sisolar cells manufactured in the world reaches 19 % in industrial conditions, and in laboratory conditions – about 25 %, therefore, the increase in efficiency of solar cells produced at «Kazakhstan Solar Silicon» LLP is an actual task.

While in the past, most of the research aimed at increasing the efficiency of solar cells was carried out on the front (sunny) side of the cell, recently the photovoltaic industry has shifted its focus to the rear (back) side. Or to be precise, today it is a lot about passivating the rear surface of a solar cell and accordingly modifying the metallization scheme. These rather simple changes adapted to standard solar cell processing entitle the produced silicon slices for a new name – PERC, which stands for Passivated Emitter and Rear Cell. Also, global trends and the power of energy produced in 2016-2020 are shifting towards PERC technology. As it was noted in [10], about 50 % of all the produced «solar» energy by 2020 will be accounted for by the PERC. Therefore, the transition from the standard Al-BSF technology (implemented at «Kazakhstan Solar Silicon» LLP) to PERC technology is a win-win proposition for the development of solar energy in the Republic of Kazakhstan.

The PERC structure is a natural progression from the standard Back Surface Field (BSF) cell architecture. The electrical and optical losses, resulting in reduced efficiency of solar cells, as described above, can be greatly reduced by applying an additional dielectric passivation layer on the rear side. Although the transition to the PERC structure only requires that a few pieces of equipment are added to the standard production line. PERC is gradually becoming the most cost-efficient choice for mass production of cells, and offers a good approach to surpass the 20 % cell efficiency level in mass production.

It is known [11] that record-breaking efficiency values of 22.04 % (for mc-Si PERC solar cells, Jinco) and 23.95 % (for mono-Si PERC solar cells) were not obtained on an industrial scale. However, the graph [11] reflects the potential and progress of this technology, both in the multi and in the mono production.

Processing PERC involves depositing a rear surface passivation film, which is subsequently opened to give way for formation of a rear contact – these are two important additional steps over Kazakhstan solar cell processing (Fig. 8). In addition, the chemical wet-bench based edge isolation step is tweaked for rear polishing. That means texturing accomplished on both sides of the wafer is removed only on the rear side by etching off the pyramid structure. The degree of polishing changes from case to case. Thus, a passivation film deposition system and a film opening system – mainly accomplished with PECVD and lasers – are additional tool sets typically hooked up to standard cell processing lines.

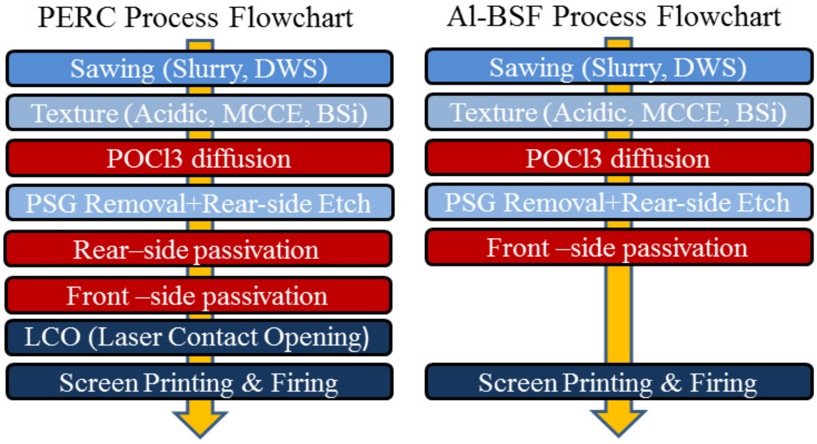


Figure 8. PERC and Al-BSF Process Flowchart

At «Kazakhstan Solar Silicon» LLP, equipment for antireflection coating (silicon nitride) deposition TWYN PECVD is presented. The PECVD process consists in the decomposition of a chemical element under the influence of plasma and temperature into individual elements in the reactor, which then settle to the surface of the wafer and enter into a chemical reaction. As a result, the thinnest film (up to 80 nm) of silicon nitride, which has the required properties, is «grown» on the front surface of the wafer. In [3], it is shown that the PECVD equipment can be modified to apply a rear passivation layer (AlOx + SixNy), while the general principle of deposition remains the same. The easiest way to open the back passivating layer is to use laser technology. Today, the photovoltaic industry has a large number of laser solutions offered by companies such as InnoLas Solutions, Rofin, 3D-Micromac, Schmid or Manz.

Conclusions

Thus, at «Kazakhstan Solar Silicon» LLP it is possible to upgrade Al-BSF standard solar cell production line to a new PERC line, which will allow the enterprise to increase the efficiency of the produced solar cells and be competitive in the global market.

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Қазақстандық кремний негізінде фотоэлектрлік түрлендіргіштердің қасиеттерін зерттеу

Күнсәулелік энергетикасын дамыту жалпыәлемдік тренд пен Қазақстан Республикасы Үкіметінің «жасыл» экономикаға көшу жөніндегі бағытқа сәйкес келетіндіктен, фотоэлектрлік түрлендіргіштердің (ФЭТ) қасиеттерін зерттеу өзекті тақырып болып табылады. Меншікті және беттік кедергі, қуаттасушының қызмет ету уақыты, шағылыстыру қабілеті, кванттық тиімділік секілді ФЭТ-нің әртүрлі қасиеттері ФЭТ алынатын тиімділігіне тікелей әсер етеді. Осы жұмыс «күнсәулелік» сапалы қазақстандық кремний негізінде әзірленетін фотоэлектрлік түрлендіргіштерді алу мен оны кешенді зерттеуге арналған. Зерттеуде қысқатолқынды диапазонда (μ-PCD) фотоөткізгіштіктің ыдырауын өлшеу әдісі, беттік және меншікті кедергіні өлшеудің 4 нүктелі әдісі, шағылу, өткізу және фотолюминесценция коэффициенттерін спектрометрлік талдау әдістері, электрондық микроскопия әдістері, сондай-ақ вольтамперлік сипаттамаларын талдау әдістері қолданылған. ФЭТ өндірісінің меңгеріп алынған әдістері сипатталған. Al-BSF стандартты желісін PERC желісіне дейін модификациялау ұсынылды.

Кілт сөздер: фотоэлектрлік түрлендіргіштер, күнсәулелік элементтер, кремний, Al-BSF құрылымы, PERC құрылымы, күнсәулелік энергетика.

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Исследование свойств фотоэлектрических преобразователей на основе казахстанского кремния

Исследование свойств фотоэлектрических преобразователей (ФЭП) является актуальной темой, поскольку развитие солнечной энергетики соответствует общемировому тренду и взятому курсу Правительства Республики Казахстан по переходу на «зеленую» экономику. Различные свойства ФЭП, такие как удельное и поверхностное сопротивление, время жизни носителей заряда, отражательная способность, квантовая эффективность непосредственно влияют на эффективность получаемых ФЭП. Настоящая работа посвящена получению и комплексному исследованию фотоэлектрических преобразователей, изготавливаемых на основе казахстанского кремния «солнечного» качества. В исследовании применены метод измерения распада фотопроводимости в микроволновом диапазоне (μ-PCD), 4-зондовый метод измерения поверхностного и удельного сопротивления, методы спектрометрического анализа коэффициентов отражения, пропускания и фотолюминесценции, метод растровой электронной микроскопии, а также методы анализа вольтамперных характеристик. Описаны освоенные методы производства ФЭП. Предложена модификация стандартной линии Al-BSF до линии PERC.

Ключевые слова: фотоэлектрические преобразователи, солнечные элементы, кремний, Al-BSF структура, PERC структура, солнечная энергетика.

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