CHARACTERISTICS OF PHOTOVOLTAIC CELLS OBTAINED FROM SOLAR GRADE SILICON USING MONOLIKE TECHNOLOGY WITH APPROACHES OF TECHNICAL AND ECONOMICAL EFFICACY, AND COMPARISON WITH THE TRADITIONAL PREPARATION METHOD

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ABSTRACT

The study investigates the potential for the production of solar cells from Kazakhstani p-type conduction, purified by a metallurgical method using the advantages of the monolike technology. According to the experimental data, it can be seen that the effective lifetime shows low indicators on the FE taken from the upper part of the ingots before the gettering process. This applies to multicrystalline silicon cells. After phosphorus diffusion, an increase in τ_{eff} can be seen, which does not depend on the material under study. As a rule, a decrease in the effective lifetime of charge carriers in silicon can occur due to the presence of a large number of metal impurities, which can create formations in the form of deposits in crystal defects or dissolve in silicon. This impurity can be interstitial iron (Fe_i), which can form additional energy levels in Eg. As a result, the recombination activity of the cell increases and τ_{eff} decreases. During phosphorus diffusion, those impurities with a sufficiently high diffusion coefficient can penetrate into the n-type layer and create electrically neutral clusters. It has been shown that silicon grown by the monolike technology has a longer carrier lifetime compared to standard mc-Si. In addition, it was shown that in the process of creating a FE, the lifetime of charge carriers increases due to the gettering effect without additional purification processes. The advantages of the developed technology were observed at the level of solar cells, manifested in an increase in efficiency and a decrease in the distribution of efficiency along the ingot height. In conclusion, it is shown that SC made of monolike silicon has a rather low degradation of efficiency when exposed to light. Silicon monolike in the near future may become a breakthrough in the photovoltaic industry due to the high potential for the production of solar cells with high efficiency and a significant reduction in production costs.

Keywords: silicon, monolike, solar cells, directional crystallization, light degradation.

1. INTRODUCTION

Modern solar cells are significantly superior in performance to batteries created in the 50s and are widely used in various areas of the national economy.

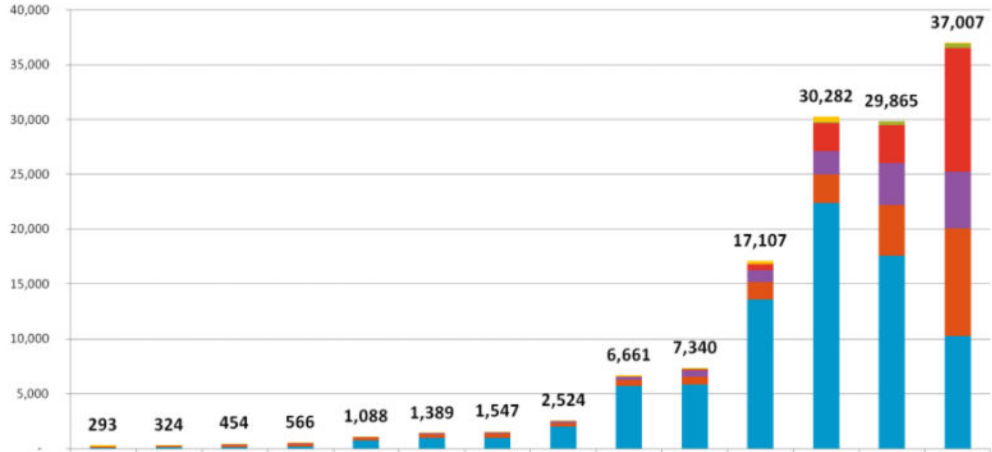
The first photocell was created in 1953, and it was a converter of radiant energy into electrical energy with a very high efficiency for this class of devices, reaching 6% [1]. A solar cell is a combination of photovoltaic modules electrically interconnected. The combination is chosen depending on the required electrical parameters such as current and voltage [2].

The electricity generated was 100 times more expensive than from a conventional grid. For nearly 20 years, solar panels have only been used for space. In 1977, the cost of electricity was reduced to $ 76 per watt cell. The efficiency was gradually increasing: 15% in the mid-90s of the last century and 20% by 2000 [3].

Silicon is an element with semiconducting properties located in group IV of the periodic system, the second most common element in nature. Its atomic weight is 28.06, and its serial number is 14[4].The melting point of crystalline silicon is 1415 ° C, and the boiling point is 2360 ° C. The electrical conductivity of silicon, depending on the type and number of impurities introduced into it, varies within fairly wide limits. Like the other three elements of group IV, silicon has a diamond-type lattice [5].

For comparatively many years, silicon has been the object of comprehensive physical researches [6]. In recent years, physicists have focused their main attention on the study of its electrical properties. During many years of research work, results have been obtained both for theory and practice. Among them, the method of obtaining silicon with a predetermined conduction mechanism - electron or hole, is of great importance, which made it possible to develop silicon detectors. An equally important result, undoubtedly, should be considered the development of a technology for introducing impurities of atoms into a silicon single crystal, which makes it possible to obtain a junction in one crystal, on the basis of which a silicon photocell with a barrier layer was created[4, 7]. On the basis of such photocells, a solar battery was made.

The manufacturing technology of a silicon photocell is rather complicated. It boils down mainly to the following operations. First, large single crystals are grown from molten silicon. Single crystals can be grown in different ways. One of them is that a seed is immersed in molten silicon and very slowly rises up. A seed, a small single crystal of a given substance, is a center around which crystallization begins. In the process of slowly raising the seed, a gradual formation of a silicon single crystal begins, which can be obtained in sufficiently large sizes. This entire process is carried out under high vacuum conditions. Silicon is heated by an induction high-frequency furnace [8].



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
🟨 ROW	88	56	80	77	29	10	105	42	76	80	284	508	-	85
🟩 MEA	-	-	-	-	1	0	0	1	1	22	46	125	365	383
🟥 China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,300
🟪 AMERICA	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,153
🟧 APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
🟦 Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,616	22,407	17,580	10,253
TOTAL	293	324	454	566	1,088	1,389	1,547	2,524	6,661	7,340	17,107	30,282	29,865	37,007

Figure-1. The use of solar panels in the world (2018-2020).

The obtained silicon single crystals are cut into thin rectangular plates. The plate has an electronic conduction mechanism. To create a photocell with a barrier layer, a system of two semiconductors with opposite conduction mechanisms is required. To do this, one of the surfaces of the plate is covered with a thin uniform layer of boron, and for some time the plate is heated in an electric furnace with continuous operation of vacuum pumps. The time of diffusion heating is selected in such a way that the boron atoms during this time have time to diffuse into the plate only for a part of its thickness [8].

One part of the silicon wafer will have hole conductivity, and the other part will have electronic conductivity. At the border between one and the other parts, a p-n junction is formed and, as a consequence of this barrier layer. On both surfaces of the silicon plate, using a special method, metal electrodes, one of which is translucent. Then the plate is placed in a mandrel with two current leads [8, 9].

Individual photovoltaic cells can be connected to each other in series and in parallel, thus obtaining a photovoltaic (solar) battery. Such a solar battery can be used in non-electrified areas to power portable radios and transmitters, telephone exchanges, etc. That is, they have an efficiency of about 6%. For a correct assessment of the capabilities of photocells with a barrier layer, it is sufficient to recall that steam engines have an efficiency of the order of 6-8%. In addition, it should be borne in mind that, unlike other energy converters, the service life of semiconductor photocells can be very long, and in some cases, practically unlimited [8, 9].

Modern solar cell production is almost entirely based on silicon. About 80% of all modules are manufactured using poly- or monocrystalline silicon, and the remaining 20% use amorphous silicon [8, 9].Crystalline photovoltaic cells are the most common and are usually blue in color with a sheen. Amorphous, or non-crystalline, are smooth in appearance and change color depending on the angle of view. Monocrystalline silicon has the best efficiency (about 14%), but it is more expensive than polycrystalline silicon, the average efficiency of which is 11%[8, 9].Amorphous silicon is widely used in small devices such as watches and calculators, but its effectiveness and long-term stability is much lower, so it is rarely used in power plants.

Several types of alternative thin-film photocells are currently in pilot development and may conquer the market in the future.

Photovoltaic cells are made of heterogeneous semiconductor materials, the main of which is silicon today. Photovoltaic cells are made from ultrapure silicon mixed in precise proportions with several other substances. The ultrapure silicon substrate from which solar cells are made is very expensive. The amount of ultrapure silicon required to make one 50 W photovoltaic module would be sufficient for the integrated circuits of about two thousand computers. In addition, solar cells contain aluminum, glass and plastic - inexpensive and reusable materials.

The highest efficiency of conversion of solar energy are monocrystalline cells (about 14%). Their service life is about 20 years [10]. The technology of manufacturing ultrapure silicon of solar-quality, which is the base material for monocrystalline solar cells, is well mastered and developed. A single crystal of silicon grows from a seed slowly drawn out of a silicon melt. The resulting rods are cut into discs with a thickness of 0.2-0.4 mm. Then the discs undergo a series of manufacturing operations that transform them into monocrystalline solar cells themselves:

- grinding, cleaning and sanding
- protective coatings;
- anti-reflective coatings;
- metallization.

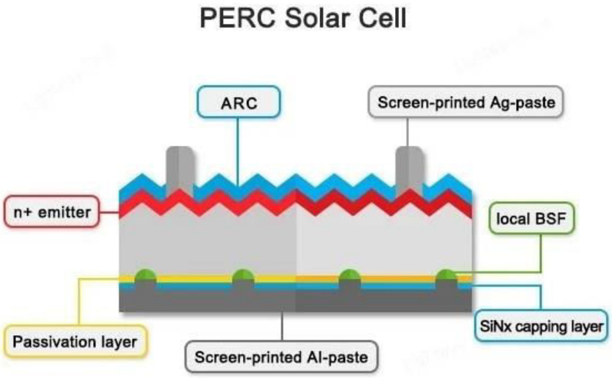


Figure-2. The difference between standard and PERC solar cells.

The main disadvantage of monocrystalline solar cells is their high cost, 50 - 70% of which is the price of silicon itself. A decrease in power during shading or strong clouds is another significant disadvantage of this photocells' type.

Modules made of polycrystalline silicon have a lower efficiency in comparison with monocrystalline (efficiency is 10-12%) and have a shorter service life in 10 years, but their cost is less due to lower energy consumption during manufacturing. In addition, the power of polycrystalline solar cells depends on shading to a lesser extent than monocrystalline ones. The formation of polycrystalline silicon occurs when the silicon melt is slowly cooled [11]. The lower efficiency is explained by the presence of regions inside the polycrystalline silicon crystal, separated by granular boundaries, which hinder the higher productivity of the elements [12].

Modules made of amorphous silicon are even less efficient than those made of crystalline silicon - their efficiency is only 6-9%, moreover, they are less durable. However, low power consumption, ease of production and its low cost, the possibility of producing large-sized elements make amorphous silicon modules in demand in the widest spheres of human activity. Amorphous silicon is widely used in the manufacture of watches and calculators, but it is inapplicable for high-power installations due to its lower stability. The «vapor phase method», which is used to make amorphous silicon, consists in the deposition of a thin film of silicon on a substrate and the application of a protective coating.

As a result of this deposition, electrically conductive *p-n* junctions are formed. Such modules are effective even in low light and cloudy conditions and are better protected from aggressive external factors. Photocells made of amorphous silicon (a-Si) are much cheaper than photocells made of crystalline silicon, since the silicon layer in them is only 0.5-1.0 microns versus 300 microns in crystalline cells. Their scope of application is much wider than that of crystalline ones: it is possible, for example, to manufacture flexible photovoltaic modules from amorphous silicon for non-standard roof elements, etc.

Currently, the most common types of thin-membrane solar cells are amorphous silicon solar cells, CIS (CIGS) and CdTe technologies. In addition to the described types of photocells, there are many less-common developments - these are gallium arsenide heterophoto converters, experiments in the field of sensitized paints and organic photocells, etc.

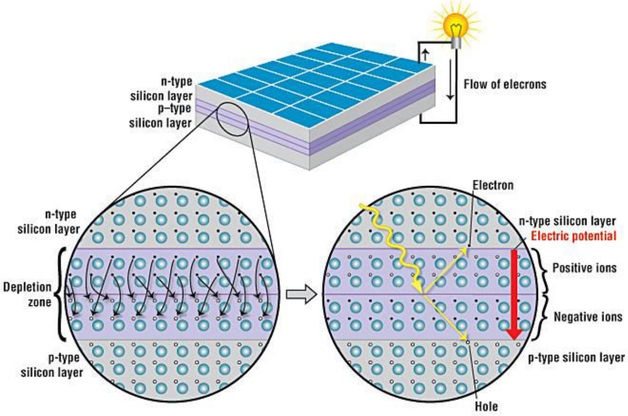


Figure-3. Schematic representation of a solar cell, showing the *n*-type and *p*-type layers, with a close-up view of the depletion zone around the junction between the *n*-type and *p*-type layers.

Currently, the main raw material for the production of solar cells is silicon of «electronic» quality (EG), which is obtained through the Siemens process [13, 14]. This process is well controlled, but requires a lot of investment and energy consumption. However, silicon with a lower quality than EG silicon is suitable for the photovoltaic industry, but it is desirable to reduce the number of crystal defects that negatively affect the transport characteristics of charge carriers [15]. This leads to a great interest in the development of other methods of silicon refining sufficient for photovoltaic production. An alternative technology, refining by physical methods, makes it possible to produce solar grade silicon (SoG-Si) at a lower cost compared to EG-Si.

So, it can stated that photovoltaic cell (solar cell) is used to generate electricity by converting solar radiation. A photocell can be considered as a diode composed of *n*-type and *p*-type semiconductors with a carrier depleted zone formed, therefore an unlit photocell is like a diode and can be described as a diode. For semiconductors having a band gap between 1 and 3 eV, the maximum theoretical efficiency can be reached 30% [3, 16]. The band gap is the minimum photon energy that can lift an electron from the valence band to the conduction band. The most common solar cells produced by the industry are silicon cells.

Silicon monocrystallins and polycrystallines. Silicon today is one of the most common elements for the production of photovoltaic modules. However, due to the low absorption of solar radiation, silicon crystal solar cells are usually made with a width of 300 μm. The efficiency of a silicon monocrystal photocell reaches 17% [17].

If photocelltaken from a polycrystal of silicon, then the efficiency for it is 5% lower than that of a single crystal of silicon [18]. The grain boundary of a polycrystal is the center for the recombination of charge carriers. The crystal size of polycrystalline silicon can vary from a few mm to one cm.

2. MATERIALS AND METHODS

Galium arsenide (GaAs). Gallium arsenide solar cells have already shown an efficiency of 25% in laboratory conditions. Gallium arsenide, developed for optoelectronics, is difficult to produce in large quantities and is quite expensive for solar cells. Gallium arsenide solar cells are used in conjunction with solar concentrators, as well as for astronautics. Thin-membrane photocell technology. The main disadvantage of silicon elements is their high cost. Thin- membrane cells are available that are made from amorphous silicon (a-Si), cadmium telluride (CdTe) or copper-indium diselinide (CuInSe2). The advantage of thin-membrane solar cells is the saving of raw materials and materials and cheaper production compared to silicon solar cells. Therefore, it can stated that thin-membrane products have prospects for use in photocells.

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Thin-film photocell technology. The main disadvantage of silicon elements is their high cost. Thin-film cells are available that are made from amorphous silicon (a-Si), cadmium telluride (CdTe) or copper-indium diselinide (CuInSe2). The advantage of thin-film solar cells is the saving of raw materials and materials and cheaper production compared to silicon solar cells. Therefore, we can say that thin-film products have prospects for use in photocells.

The disadvantage is that some materials are quite toxic, so product safety and recycling play an important role. In addition, telluride is an exhaustible resource compared to silicon. The efficiency of thin-film photocells reaches 11% (CuInSe2) [19].

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Physical methods completely exclude the use of chlorosilanes. SoG-Si is produced using incoming raw materials and consumables with a low content of impurities: reductant, quartz, etc. with further use of physical and physicochemical conversions - slag refining, acid leaching and directional crystallization (DC). Therefore, many world manufacturers increase or switch to the production of «solar» silicon by physical methods. The main production leaders, namely, Elkem (Norway), Waker (Germany), PhotoSil (France), SolSilc (Holland), CaliSolar (USA), CPI (USA) and SEMCO ENGINEERING (France) have implemented pilot and / or industrial projects obtaining SOG-Si by the methods above.

Another aspect in the production of solar cells is the competition between monocrystalline silicon and multicrystalline silicon (MK-Si). Monocrystalline silicon is usually grown by the Czochralski method (Cz-Si). The main advantage of Cz-Si is associated with its higher structural perfection; however, it is significantly more expensive than MK-Si. Both technologies involve the use of quartz crucibles. To increase productivity in the production of MK-Si, furnace designs are gradually improved, and crucible sizes are increased. Currently, crucibles of the sixth generation (Gen6) are used, which have a size of 1x1 m2 and the weight of the grown ingot reaches 650-800 kg, which significantly reduces the cost of silicon production.

In the process of producing monolike ingots, the same crucibles are used for producing MK-Si ingots, but, in contrast to the MK-Si technology, monocrystalline silicon seeds are laid on the bottom of the crucible.

Monolike silicon is also called quasi-monocrystalline silicon because it combines the properties of traditional Cz-Si substrates (Figure-4) and multicrystalline silicon substrates for solar cells, namely the high solar cell efficiency offered by Cz-Si, lower cost, high performance, and square shape characteristic of MK-Si [19].

Figure-4. Monolike G6 (600 kg) ingot cut into 2 pieces to show the structure.

In the process of melting the silicon raw material, a proper temperature regime is selected to avoid the melting of the seeds. The directional crystallization process begins with seeds and allows epitaxial growth of a single crystal structure (Figure-4). Usually, seeds with a crystallographic orientation of <100> are chosen, since this orientation is optimal for texturing the surface of the wafers, which increases the absorption of light by the solar cells and increases its efficiency.

2.1 Raw Materials and Technology for the Production of Silicon Ingots

Silicon obtained at the MK KazSilicon LLP plant according to the method, described Mukashev [17] was used as a raw material for the manufacture of photovoltaic cells. Table-1 shows the concentration of boron and phosphorus impurities, as well as metals at each stage of the production of silicon of «solar» quality, including the feedstock.

Table-1. Average concentrations of dopants in quartzite and "Kazakhstani" silicon after all stages of production*.

Material type	Impurity concentration, ppm wt		
	Boron	Phosphorus	Metals
Quartz	1,3	0,32	125
Metallurgical silicon (MG)	15,4	68	4000
Purified MG (UMG)	<5	8	2500
«Solar» silicon quality	0,2	0,57	<3

For the production of solar cells, 2 silicon ingots were grown by the directional crystallization method in a special PV 600 furnace from ECM (France) and weighing ~ 450 kg, each ingot had a p-type conductivity [20]. One ingot, which was grown according to the standard technology, without the use of seeds, was used as a reference. When growing the second ingot, seeds were laid on the bottom of the crucible and the growth took place using the monolike technology.

The growth of polycrystalline silicon ingots takes several stages with a duration of about 78 h. Initially, silicon is heated to a melting temperature of 1423 °C until a homogeneous melt is obtained. At the same time, changes were made to the temperature regime of the second ingot taking into account the inadmissibility of the seed melt. Further, directional crystallization is carried out from the bottom to the top of the ingot by controlling the furnace heaters.

The resulting silicon ingots are cut into square blocks, which are subsequently cut into wafers 156 × 156 mm in size and 180 μm thick. Next, the plates were selected according to the height of some ingots in order to measure the effective lifetime of charge carriers (τ_{eff}) and manufacture solar cells from them.

3. MANUFACTURING OF SOLAR CELLS

The production of solar cells for two types of ingots was carried out according to the standard Al-BSF technology, according to which the surface of the solar cell is an n-type phosphorus emitter. The surface is additionally coated with an amorphous (SiNx: H - silicon nitride) antireflection coating. The bottom of the solar cell is an aluminum contact, obtained by screen printing by firing a special paste based on aluminum, on which charge carriers are collected, as well as on the silver top contact. The stages of production of solar cells according to the Al-BSF architecture are shown in Figure-5.

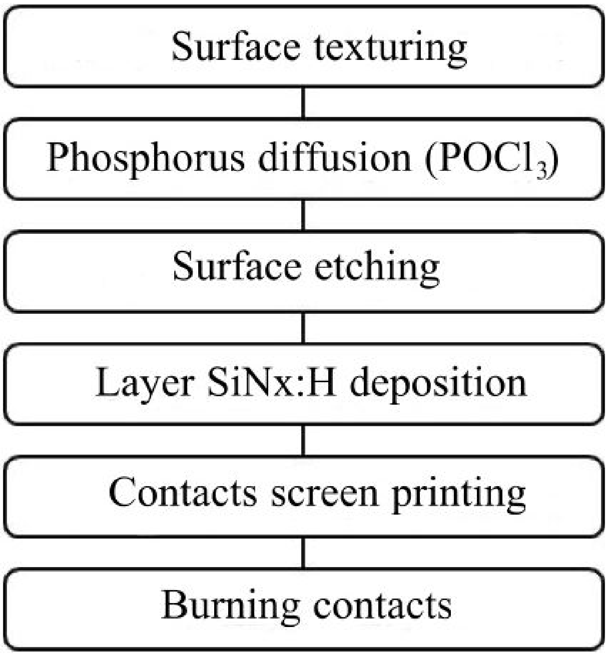

Figure-5. Scheme of solar cell production using Al-BSF technology.

Measurements of the lifetime on the SC were carried out at several different points of the samples under study using the QssPC method [21].

4. RESULTS AND DISCUSSIONS

4.1 Dependence of τ_{eff} on Gettering

Figure-6 (a, b) shows the results of measurements of τ_{eff} for silicon cells of both types of silicon, depending on the gettering process.

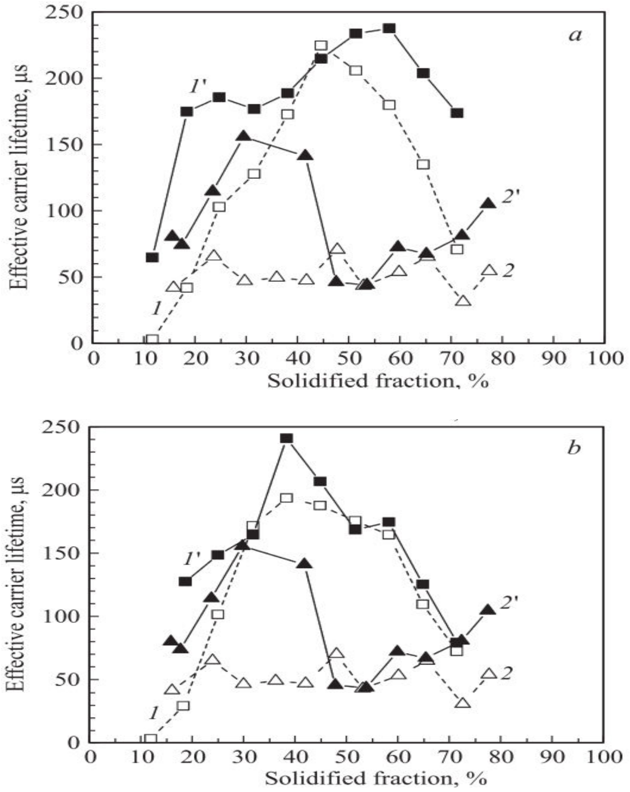

Figure-6. Comparison of the dependence of τ_{eff} on plates of quasi-single-crystal silicon - central (a), last (b) blocks and mc-Si (a, b) of the ingot fraction.

1 - monolike-Si before and 1' after gettering, 2 - mc-Si before the process and 2' after the gettering process.

According to the experimental data, it can be seen that the effective life time shows low indicators on the FE taken from the upper part of the ingots before the gettering process. This applies to multicrystalline silicon cells. After phosphorus diffusion, an increase in τ_{eff} can be seen, which does not depend on the material under study.

As a rule, a decrease in the effective lifetime of charge carriers in silicon can occur due to the presence of a large amount of metal impurities, which can create formations in the form of deposits in crystal defects or dissolve in silicon. This impurity can be interstitial iron (Fe_i), which can form additional energy levels in Eg. As a result, the recombination activity of the cell increases and τ_{eff} decreases. During phosphorus diffusion, those impurities with a sufficiently high diffusion coefficient can penetrate into the n-type layer and create electrically neutral clusters.

It can be seen from the presented figures that for quasi-single-crystal silicon, τ_{eff} is higher due to the initial high values of τ_{eff} and τ_0 before gettering (Figure-3-a, b). The high value of τ_0 of quasi-single-crystal silicon can be explained by the better structural quality of the ingot and a small amount of metallic impurities in the silicon wafer. This is reflected in more detail in (Bothe and Schmidt, 2006). The values of τ_{eff} and τ_0 decrease with the growth of the ingot, which is associated with an increase in the density of crystallographic defects during the growth of the ingot and an increase in the concentration of impurities due to segregation, which is confirmed by measurements of the values of $\tau_{eff}$and defects in (Bothe and Schmidt, 2006). The increase in τ_{eff} after gettering is lower for wafers from a side block of quasi-multicrystalline silicon and all mc-Si wafers (Figure-6, a, b). This circumstance suggests that the absence of an increase in gettering τ_{eff} may mean that τ_{eff} depends more on crystallographic defects than on impurity concentrations.

4.2 Influence of the Type of Material on the Efficiency of the Solar Cell

The light volt-ampere characteristics (CVCs) were measured on the SC under study at standard temperature and illumination (AM1.5G, 0.1 W cm-2, 25 ° C). The results of the I - V characteristic were such parameters of the solar cell as the short-circuit current density (J_{sc}), the open circuit voltage (V_{oc}), the efficiency (η), and the fill factor (FF).

Figures 7 and 8 show the dependence of J_{sc} and V_{oc} of monolike-Si and mc-Si solar cell ingots on the ingot height. The J_{sc} and V_{oc} readings are rather strongly dependent on τ_{eff} and correlate well with it. Based on the results, it can be seen that the values of $J_{sc}$and V_{oc} are higher for solar cells made of quasi-single-crystal silicon due to the higher values of τ_{eff}.

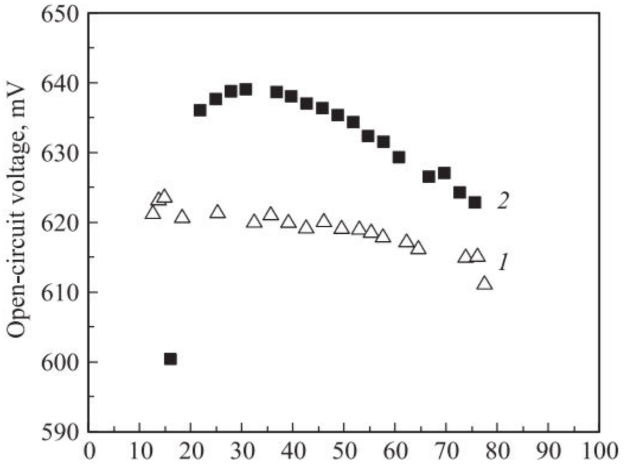

Figure-7. Dependence of V_{oc}on the ingot height for SC made of mc-Si (1) and monolike-Si (2).

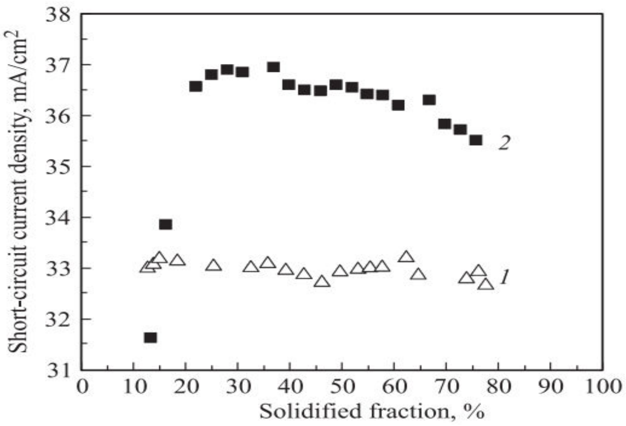

Figure-8. Dependence of J_{sc} on the ingot height for SC made of mc-Si (1) and monolike-Si (2).

Figure-9 shows the dependence of the efficiency of the solar cell on the height of ingots manufactured using the Al-BSF technology. Monolike-Si plates have slightly higher efficiency. The maximum efficiency for solar cells made from monolike-Si has exceeded 18%.

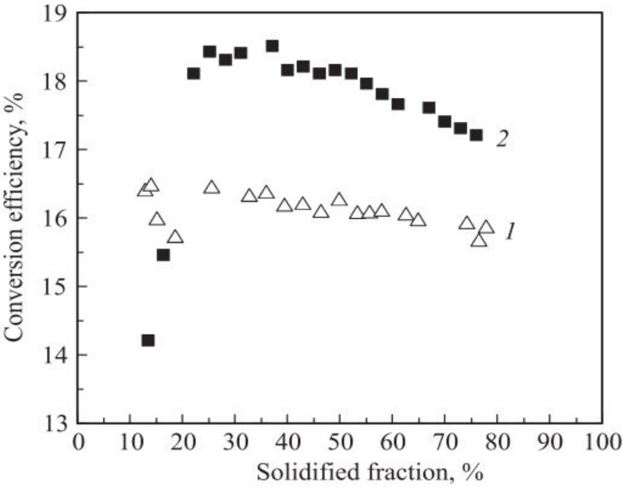

Figure-9. Efficiency versus ingot height for mc-Si (1) and monolike-Si (2) solar cells.

4.3 Light Degradation

Additionally, the I-V characteristics were measured on the SC after the light degradation test. To study the effect of degradation of solar cells (LID, light induced degradation) under illumination, solar cells with the highest efficiency were used. The LID measurements were carried out on a setup that records the change in V_{oc} at a constant temperature (65 ° C) and illumination (43 mV, ~ 1.1 "Sun") every second.

These studies are important because of the formation of boron-oxygen (B-O) complexes upon exposure to light. These complexes, in turn, are electrically active recombination centers and can significantly reduce the efficiency of solar cells [22].

Table-2 shows the results of the LID tests performed. To confirm the stability of measurements, a reference SC without degradation process was used. It was found that the average value of the relative degradation of the efficiency is ~ 1%. The results obtained show an insignificant effect of LID on the efficiency of SC made of monolike-Si, which correlates well with the theoretical data on the formation of B-O complexes at an oxygen concentration of> 3 × $10^{17} cm^{-3}$. According to measurements, the concentration of interstitial oxygen [Oi] in monolike-Si (Figure-7) does not exceed 3 × $10^{17} cm^{-3}$ for a part of the ingot used to create solar cells. In contrast to silicon grown by the Czochralski technology, in which [Oi] reaches ~ 8 × $10^{17} cm^{-3}$, silicon grown by the monolike technology is less susceptible to the formation of B - O complexes and, therefore, to the degradation of the solar cell efficiency upon exposure to sunlight.

Table-2. Relative losses of the main electrical characteristics V_{oc}, J_{sc}, FF, η for solar cells made from monolike-Si.

SC position along ingot height, %	**Relative losses,%**			
	ΔV_{oc}	**ΔJ_{sc}**	**ΔFF**	**Δη**
Reference SC	0	0,2	0,1	0
20	0,2	0,3	0,6	0,6
47	0,2	0,3	0,5	1
69	0,4	0,7	1,4	1,4

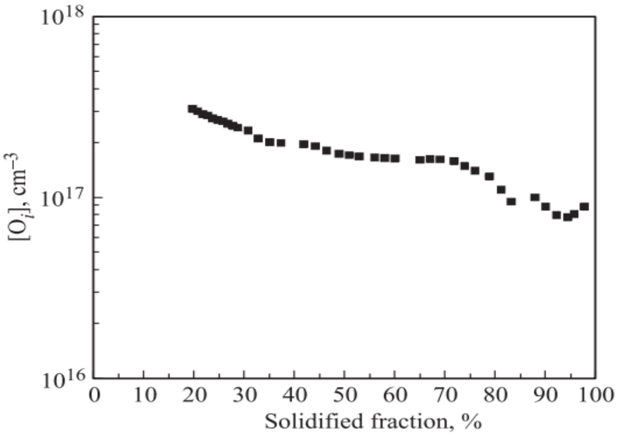

Figure-10. Change in Oi concentration along the height of a monolike-Si ingot.

On the other hand, on the studied SC, the LID effect increases with an increase in the crystallization fraction and, therefore, with a decrease in [Oi], which may indicate that the LID effect is more associated with other processes and mechanisms than the formation of B - O complexes. In recently published works [23, 24], it was reported that impurities of metals, such as copper, form electrically active precipitates in the bulk of silicon when exposed to illumination and can cause degradation of the electrical characteristics of SC. The literature also presents data on the degradation of SC from mc-Si under illumination without explaining the reasons for this phenomenon [25]. In addition, it's reported that on the influence of the SC architecture on the degradation effect under illumination [26]; it is shown that SC with a passivated surface is more sensitive to degradation. The obtained LID results have not yet been explained and require further analysis.

5. CONCLUSIONS

The paper investigates the potential for the production of solar cells from Kazakhstani p-type conduction, purified by a metallurgical method using the advantages of the monolike technology. It has been shown that silicon grown by the monolike technology has a longer carrier lifetime compared to standard mc-Si. In addition, it was shown that in the process of creating a FE, the lifetime of charge carriers increases due to the gettering effect without additional purification processes. The advantages of the developed technology were observed at the level of solar cells, manifested in an increase in efficiency and a decrease in the distribution of efficiency along the ingot height. It is shown that SC made of monolike silicon have a rather low degradation of efficiency when exposed to light. In conclusion, silicon monolike in the near future may become a breakthrough in the photovoltaic industry due to the high potential for the production of solar cells with high efficiency and a significant reduction in production costs.

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