UDC 621
DOI: 10.15587/1729-4061.2022.265771

CHARACTERISTICS OF PHOTOVOLTAIC CELLS USING MONOLIKE TECHNOLOGY WITH TECHNICAL AND ECONOMICAL EFFICACY, AND COMPARISON WITH THE TRADITIONAL PREPARATION METHOD

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The survey explores the potential for the creation of sun oriented cells from Kazakhstani p-type semiconductors, filtered by a metallurgical strategy utilizing the benefits of the mono-like innovation. As per the exploratory information, it tends to be seen that the successful lifetime shows low markers on the solar element taken from the upper piece of the ingots before the gettering system. This applies to multi-glasslike silicon cells. After phosphorus dispersion, an expansion in complete viability should be visible, which doesn't rely upon the material under study. Generally speaking, a decrease in the effective lifetime of charge carriers in silicon can happen because of the presence of a lot of metal impurities, which can create formations in the form of deposits in crystal defects or dissolve in silicon. It is shown that silicon developed by the mono-like innovation has a more drawn out transporter lifetime contrasted with standard mc-Si. Likewise, it was shown that during the time spent making a solar element, the lifetime of charge transporters builds because of the gettering impact without extra refinement processes. The benefits of the created innovation were seen at the degree of sunlight based cells, appeared in an expansion in proficiency and a reduction in the conveyance of effectiveness along the ingot level. All in all, it is shown that a solar cell made of mono-like silicon has a fairly low corruption of productivity when presented to light. Mono-like silicon sooner rather than later may turn into a forward leap in the photovoltaic business because of the great potential for the development of sunlight-based cells with high proficiency and a critical decrease in expenses

Keywords: silicon, mono-like, solar cells, directional crystallization, light degradation, total efficacy, output voltage, photovoltaic, crystalline, conductivity

Received date 22.07.2022
Accepted date 03.10.2022
Published date 30.10.2022

***How to Cite**: Kalygulov, D., Plotnikov, S., Lay, P. (2022). Characteristics of photovoltaic cells using monolike technology with technical and economical efficacy, and comparison with the traditional preparation method. Eastern-European Journal of Enterprise Technologies, 5 (5 (119)), 6–15. doi: https://doi.org/10.15587/1729-4061.2022.265771*

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.

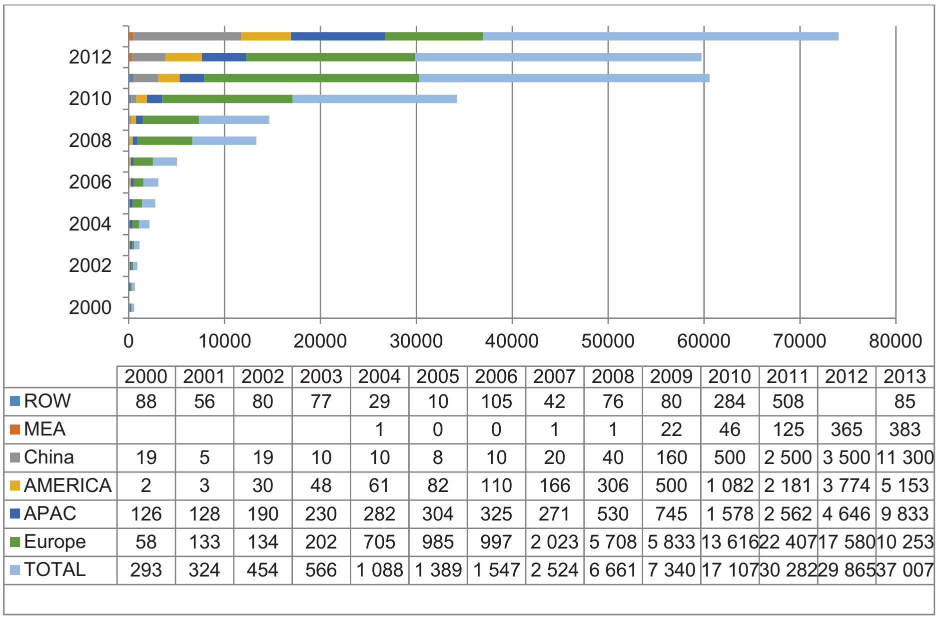
The first photocell was created in 1953, and it was a converter of radiant energy into electrical energy with very high efficiency for this class of devices, reaching 6 % [1]. A solar cell is a combination of photovoltaic modules electrically interconnected. The combination is chosen depending on the 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 1,415 °C, and the boiling point is 2,360 °C. The electrical conductivity of Si, depending on the type and number of impurities introduced into it, varies within fairly wide limits. Like the other three elements of group IV, Si has a diamond-type lattice [5].

For comparatively many years, silicon has been the object of comprehensive physical research [6]. In recent years, physicists have focused their main attention on studying its electrical properties. During many years of research work, results have been obtained both for theory and practice.

Among them, the method of obtaining Si 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, is the development of a technology for introducing impurities of atoms into a single Si crystal, which makes it possible to obtain a junction in one crystal, on the basis of which a Si photocell with a barrier layer was created [4, 7]. On the basis of such photocells, a solar battery was made.



	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

Fig. 1. The use of solar panels in the world (2018–2020)

The manufacturing technology of a Si-based 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 Si 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 the slow rising of the seed, a gradual formation of a single crystal begins, which can be obtained in sufficiently large sizes. This entire process is carried out under high vacuum conditions. Si is heated by an induction high-frequency furnace [8].

Silicon is, by a long shot, the most widely recognized semiconductor material utilized in sun-based cells, addressing roughly 95 % of the modules sold today. It is the second most bountiful material on Earth (after oxygen) and the most widely recognized semiconductor in microchips. Glass-like cells are made of Si particles associated with each other to shape a precious stone grid. This cross-section gives a coordinated construction that makes a change of light into power more proficient [9]. Sunlight-based cells made from silicon give a mix of high proficiency, minimal expense, and a long lifetime. Modules are supposed to keep going for a considerable length of time, delivering over 80 % of their unique power after this time.

Another procedure to further develop PV cell proficiency is layering different semiconductors to make multi-junction sun-powered cells. These cells are heaps of various semiconductor materials instead of single-intersection cells with just a single semiconductor [10]. Each layer has an alternate bandgap, so they each retain an alternate piece of the sun-oriented range, utilizing daylight than single-intersection cells. Multi-junction sun-powered cells can arrive at record proficiency levels because a layer catches the light that does not get consumed by the principal semiconductor layer underneath it.

Fixation PV, or CPV, centers daylight onto a sun-powered cell by utilizing a mirror or focal point. By centering daylight onto a little region, less PV material is required. PV materials become more proficient as the light becomes more thought, so the most elevated, generally speaking, efficiencies are acquired with CPV cells and modules [11]. In any case, more costly materials, producing procedures, and capacity to follow the development of the sun are required, so exhibiting the important expense advantage over the present high-volume silicon modules has become testing. Fig. 1 shows the use of solar panels in the world during 2018–2020.

The obtained Si 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. There is a contrast between the standard emitter and passivated emitter and the rear contact solar cells, which are shown in Fig. 2.

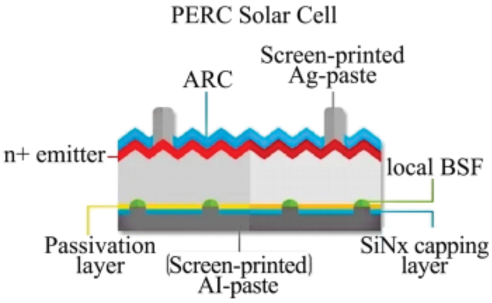


Fig. 2. The difference between standard and passivated emitter and rear contact solar cells

The time of diffusion heating is selected in such a way that the boron atoms during this period have time to diffuse into the plate only for a part of its thickness [12].

2. Literature review and problem statement

Solar energy is considered a crucial type of renewable energy that is readily available, cheap, and has no adverse effects on the environment. As a result, solar cells have attracted considerable attention, characterized by the invention of new technologies to generate more solar energy due to the abovementioned advantages. Over the 50 years that photovoltaic technology has existed, a special focus has been on advancing its efficacy.

Efficacy is a vital factor in realizing sufficient solar energy, rendering analysis of the factors that influence the efficacy of PV cells, including removal of impurities or gettering, type of material, and alteration of materials by light, a valuable study. The purity of a PV material is a significant efficacy-limiting factor in it because developed solar cell devices are extremely sensitive to the impurities in material wafer bulk [13], which in this case is the mono-crystalline silicon. However, silicon materials used in PV cells are prone to contamination, owing to the fact that gettering them is quite expensive, and the fabrication process, particularly in mass production, is vulnerable to impurities [13]. Despite these high costs incurred when purifying silicon, it still remains the main raw material for the production of solar cells, "electronic"-grade (EG) silicon, which is obtained through the Siemens process [14–17]. This process is well controlled but requires a lot of investment and energy consumption. In this regard, investigating the process of silicon purification and its effect on the efficacy of silicon-made solar cells is vital because it can give insight into alternative methods of silicon refining sufficient for photovoltaic production. An alternative technology, refining by physical methods, would make it possible to produce solar-grade silicon (SoG–Si) at a lower cost compared to EG–Si.

Alongside gettering, the type of material and light degradation constitute other vital determinants of PV cells' efficacy. Consequently, gaining actionable insights into the influence of material type, in terms of solar energy harnessing and light degradation capacity, on the efficacy of PV solar cells is important to aid in effective integration with an alternative method of refining a specific type of silicon, such as mono-like Si and mc-Si, to realize greater efficacy in cost and the output energy. Similarly, gaining insights into the best practices for light degradation using the silicon-type material established to exhibit favorable photovoltaic characteristics.

According to the literature study, a photovoltaic (PV) cell, also known as a solar cell, can either reflect, absorb, or pass-through light that strikes it. The semiconductor material that makes up the PV cell can conduct electricity more effectively than an insulating material but not as effectively as a know best like a metal. In PV cells, a variety of semiconductor materials are employed [13].

When a semiconductor is exposed to light, the light's energy is absorbed and transferred to the semiconductor's negatively charged electrons. The additional energy enables the electrons to conduct an electrical current through the material [7, 14].

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.

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 about 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 [15].

Modern solar cell production is almost entirely based on silicon. About 80 % of all modules are manufactured using poly- or mono-crystalline silicon, and the remaining 20 % use amorphous silicon. Crystalline photovoltaic cells are the most common and are usually blue in color with sheen. Amorphous, or non-crystalline, are smooth in appearance and change color depending on the angle of view. Mono-crystalline silicon has the best efficiency (about 14 %), but it is more expensive than polycrystalline silicon, the average efficiency of which is 11 % [15]. Amorphous silicon is widely used in small devices such as watches and calculators, but its effectiveness and long-term stability are 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 [16]. 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 is in mono-crystalline cells (about 14 %). Their service life is about 20 years [10, 16]. The technology of manufacturing ultrapure solar-grade silicon, which is the base material for mono-crystalline 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 to 0.4 mm. Then the discs undergo a series of manufacturing operations that transform them into mono-crystalline solar cells themselves:

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

The main disadvantage of mono-crystalline 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 compared to mono-crystalline (efficiency is 10 to 12 %) and have a shorter service life of 10 years, but their cost is lower due to lower energy consumption during manufacturing. In addition, the power of polycrystalline solar cells depends on shading to a lesser extent than mono-crystalline ones. The formation of polycrystalline silicon occurs when the silicon melt is slowly cooled [17]. 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.

Modules made of amorphous silicon are even less efficient than those made of crystalline silicon. Their efficiency is only 6 to 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 those made of crystalline silicon, since the silicon layer in them is only 0.5 to 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.

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 hetero-photo converters, experiments in the field of sensitized paints and organic photocells, etc.

So, it can be stated that photovoltaic cells (solar cells) are 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 reach 30 % [3, 18]. 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 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 mono-crystal photocell reaches 17 % [18].

If the photocell is taken from a poly-crystal of silicon, then its efficiency is 5 % lower than that of a single crystal of silicon. The grain boundary of a poly-crystal is the center for the recombination of charge carriers. The crystal size of polycrystalline silicon can vary from a few mm to one cm. Overall, it has already been established that PV solar cells' efficacy is influenced by impurities in the PV cells' material, material type, and the mechanism for light degradation, which can be leveraged to realize and inform existing technologies for fabricating PV cells to develop highly efficient cells that generate sufficient solar energy that is environmentally friendly and inexpensive.

3. The aim and objectives of the study

The aim of the study is to investigate the characteristics of photovoltaic cells using mono-like technology with technical and economical efficacy, and comparison with the traditional preparation method.

To achieve the aim, the following objectives will be accomplished:

– to prove that the more purified/gettered mono-crystalline sun-powered chargers are exceptionally productive by how much current solar energy/current they generate to have a clear insight on the effect of impurities on PV cells' efficacy;

– to determine the dependence on short-circuit current density and open circuit voltage of mono-like Si and mc-Si solar cells to find the influence of material type on the efficacy of the two solar cells because they are made up of different materials;

– to analyze the effect of degradation on the efficacy of solar cells using light induced degradation under illumination using a reference SC that has not undergone degradation to confirm the validity of the measurements.

4. Materials and methodology

Gallium 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 desalinize (CuInSe2). The advantage of thin-membrane solar cells is the saving of raw materials and cheaper production compared to silicon solar cells. Therefore, it is stated that thin-membrane products have prospects for use in photocells.

If the photocell is taken from a polycrystalline of silicon, the efficiency for it is 5 % lower than that of a single crystal of silicon. The grain boundary of a poly-crystal is the center for the recombination of charge carriers. The crystal size of polycrystalline silicon can vary from a few mm to one cm.

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].

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 mono-crystalline silicon and multi-crystalline silicon (MK–Si). Mono-crystalline 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 [20]. 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 1×1 m^2 and the weight of the grown ingot reaches 650–800 kg, which significantly reduces the cost of silicon production.

So, the comparison of the n-type and p-type layers with a schematic role is given below in Fig. 3.

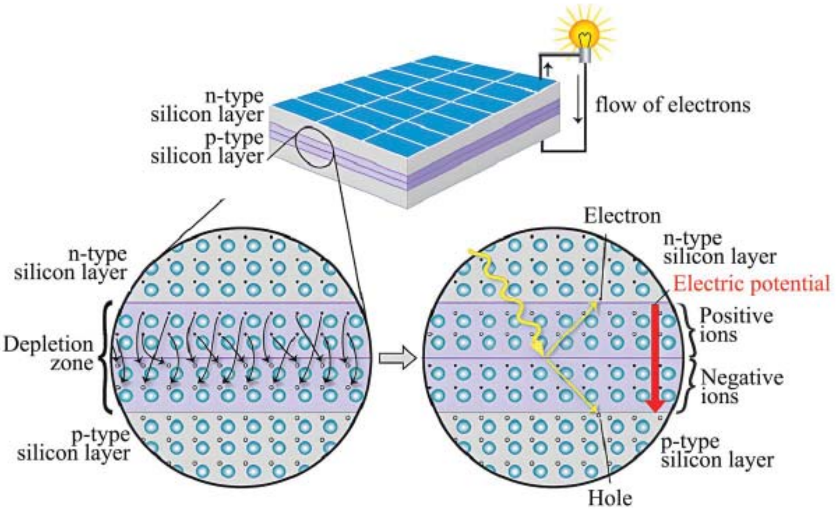


Fig. 3. Schematic representation of a solar cell, showing the *n*-type and *p*-type layers, with a close-up view of the depletion zone around the junction between the *n*-type and *p*-type layers

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

Mono-like silicon is also called quasi-mono-crystalline silicon because it combines the properties of traditional Cz–Si substrates (Fig. 4) and multi-crystalline 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 [20].

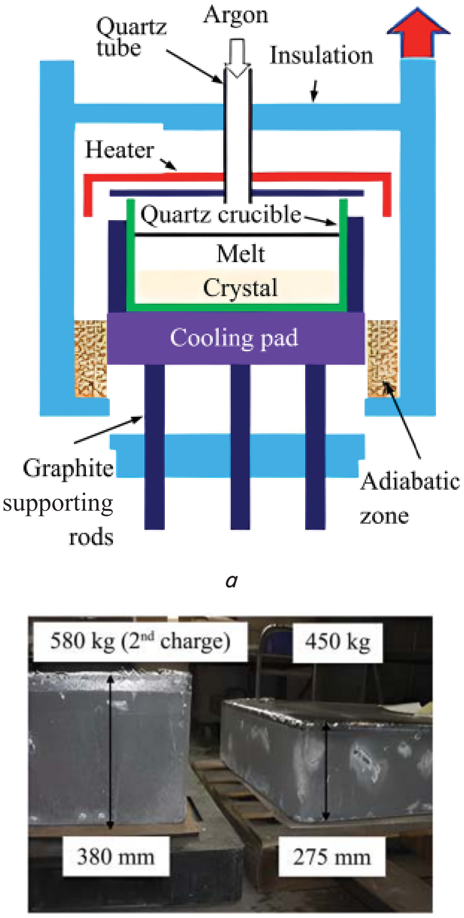
The utilization of G sheets as a dopant has likewise been examined; specifically, it has been added to PEDOT: PSS arrangements in isopropyl liquor to get a material with a conductivity many times higher and with a straightforwardness similar to ITO. By dissolving PEDOT: PSS in the liquor, the conductivity is worked on because of charges overabundance, yet the unpleasantness declines and the surface deformities are expanded. Endless supply of the G sheets, the mechanical strength and trustworthiness of the entire layer are moved along.

The expansion of rGO to PEDOT: PSS as HTL in crossover Si-natural cells (HSCs) has additionally been contemplated [16, 21]. The mix of rGO with PEDOT does not just give new courses to the charge transport in the HTL that work on the portability and productivity in the assortment of the transporters; in addition, it smothers the recombination of the electrons at the connection point. Additionally, the rGO goes about as an antireflection covering and decreases the reflectance of PEDOT, hence working on the presentation of the phones. By and large, the expansion of rGO worked on the electric conductivity of the PEDOT: PSS by 35 %, and with a convergence of 2 mg/mL, an effectiveness of 11.95 % was accomplished. In any case, an overabundance of rGO can prompt a quicker cell weakening because of the development of extra deformities.

G, GO functionalized with Li or rGO can be added to increment productivity in perovskite cells. The thought is that one or the other adds or supplants TiO_2 by one of these nanomaterials, prompting a proficiency on account of Li-GO of 11.8 % [13]. The improvement is credited to the presence of G, which diminishes the recombinations of the electron openings. Further, the rGO/PEDOT: PSS composite can be utilized as an HTL layer in this cell [17, 22]. The utilization of rGO barely changes the surface harshness, consequently inclining toward the statement of the perovskite safeguard and working on the connection point. With an ideal rGO:PEDOT:PSS 1:1 proportion, the greatest proficiency of 10.3 % was gotten [17, 18]. Moreover, rGO can be utilized as an intensity sink to expand the valuable life by staying away from mechanical burdens brought about by heat.

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 (Fig. 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.

Silicon obtained at the MK KazSilicon LLP plant according to the method described by Mukashev 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 "solar"-grade silicon, including the feedstock.



a

b

Fig. 4. Mono-like G6 ingot: *a* – mono-like G6 ingot; *b* – mono-like G6 ingot cut into 2 pieces to show the structure

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	4,000
Purified MG (UMG)	<5	8	2,500
"Solar" – grade silicon	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 [22].

One ingot, 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 mono-like 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 1,423 °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, total efficacy and manufacture solar cells from them.

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 Fig. 5 below.

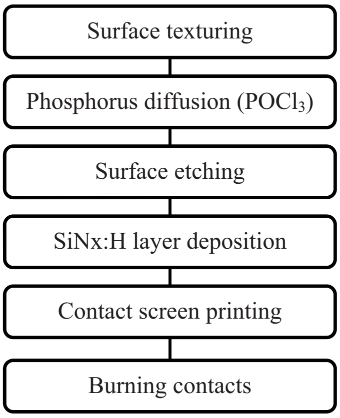


Fig. 5. Scheme of solar cell production using Al-BSF technology

Measurements of the lifetime on the SC were carried out at several different points of the samples under study using the QssPC method [21, 22].

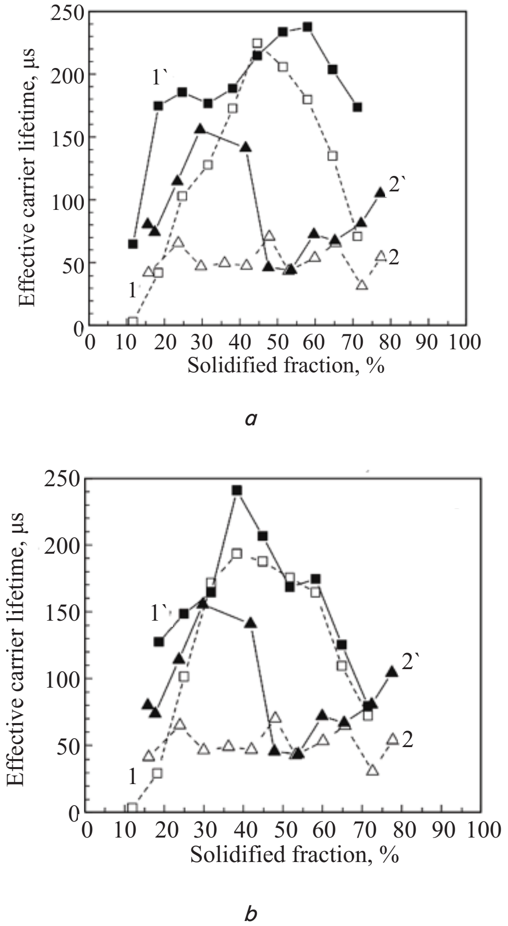
5. Results of comparative studies between different kinds of solar cells

5. 1. Dependence of total efficacy on gettering

The results indicate that few sunlight-powered chargers are evaluated at sequential voltages than others of a similar wattage worth, and this influences how much current is accessible. Different boundaries likewise significant are the open circuit voltage and short-out current evaluations according to a well-being perspective, particularly the voltage rating. A variety of six boards in series, while having an ostensible 72 volt (6×12) rating, might create an open-circuit voltage of north of 120 volts DC, which is all that could be needed to be hazardous.

Photovoltaic I-V qualities bend to give the data expected to us to design a sun-based power cluster with the goal that it can work as close as conceivable to its greatest pinnacle power point. The pinnacle power point is estimated as the PV module delivers its most extreme measure of force when presented to sunlight-based radiation identical to 1000 watts for every square meter, 1000 W/m^2 or 1 kW/m^2.

Fig. 6, *a*, *b* shows the results of measurements of total efficacy for silicon cells of both types of silicon, depending on the gettering process.



a

b

Fig. 6. Comparison of the dependence: *a* – total efficacy on plates of quasi-single-crystal silicon central; *b* – blocks and mc-Si (a, b) of the ingot fraction; 1 mono-like Si before and 1' after removal of impurities, 2 mc-Si before the process and 2' after the removal of impurities process

According to the experimental data, it can be seen that the effective lifetime shows low indicators on the SE taken from the upper part of the ingots before the removal of impurities process. This applies to multi-crystalline silicon cells. After phosphorus diffusion, an increase in total efficacy 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, which can form additional energy levels in e. g. As a result, the recombination activity of the cell increases and total efficacy 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, total efficacy is higher due to the initial high values of total efficacy and initial temperature before the removal of impurities (Fig. 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. The values of total efficacy and initial temperature 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 total efficacy and defects. The increase in total efficacy after the removal of impurities is lower for wafers from a side block of quasi-multi-crystalline silicon and all mc-Si wafers (Fig. 6). This circumstance suggests that the absence of an increase in the removal of impurities total efficacy may mean that total efficacy depends more on crystallographic defects than on impurity concentrations. 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 is reported on the influence of the SC architecture on the degradation effect under illumination [26]; it is shown that SC with a passivized surface is more sensitive to degradation. The obtained LID results have not yet been explained and require further analysis. Perovskite sunlight powered chargers appear to be the material representing things to come as they can possibly cost not as much as silicon and they are likewise more lightweight. Recent MIT research has consolidated perovskites with silicon cells, making a mixture that is productive and could be less expensive than customary silicon just boards. A few organizations are beginning up to make and sell perovskite-silicon pair cells.

5. 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, the open-circuit voltage, the efficiency (η), and the fill factor (FF).

Fig. 8, 9 show the dependence of short-circuit current density and open-circuit voltage of mono-like Si and mc-Si solar cell ingots on the ingot height. The short-circuit current density and open-circuit voltage readings are rather strongly dependent on total efficacy and correlate well with it. Based on the results, it can be seen that the values of short-circuit current density and output voltage are higher for solar cells made of quasi-single-crystal silicon due to the higher values of total efficacy. So, the dependence of total output voltage on the ingot height for SC made of mc-Si and mono-like Si is shown in Fig. 7.

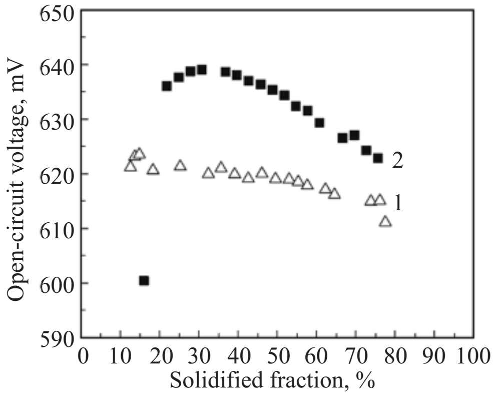


Fig. 7. Dependence of total output voltage on the ingot height for SC made of mc-Si (1) and mono-like Si (2)

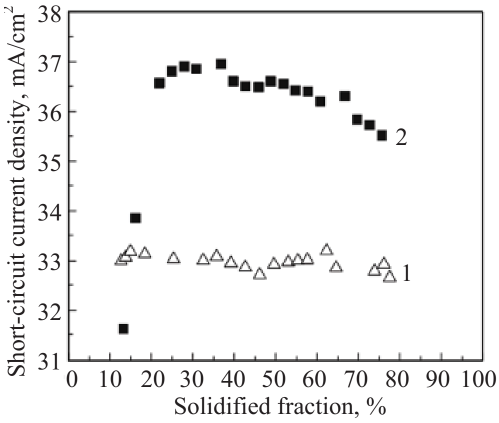


Fig. 8. Dependence of mc-Si (1) and mono-like Si (2)

Fig. 8 shows the dependence of the efficiency of the solar cell on the height of ingots manufactured using the Al-BSF technology. Mono-like Si plates have a slightly higher efficiency. The maximum efficiency for solar cells made from mono-like Si has exceeded 18 %.

According to the charts above, the height of ingots decreases with the fraction of the solidified content in relation to the efficiency of conversion. The most extreme power point of a sun-based cell is situated close to the curve in the I–V qualities bend. The relating upsides of Vmp and Imp can be assessed from the open-circuit voltage and the short-circuit current: Vmp≅(0.8–0.90)Voc and Imp≅(0.85–0.95) Isc. Since sun-based cell yield voltage and current both rely upon temperature, the genuine result power will shift with changes in surrounding temperature.

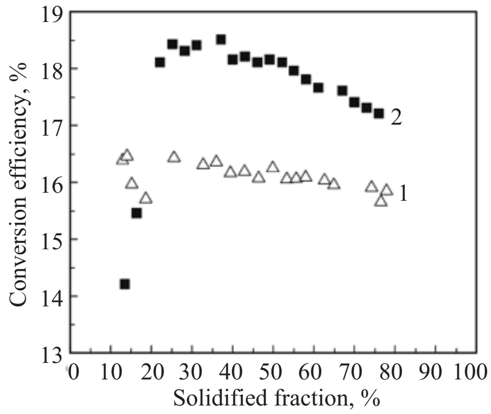


Fig. 9. Efficiency versus ingot height solar cells for: 1 – mc-Si ; 2 – mono-like Si

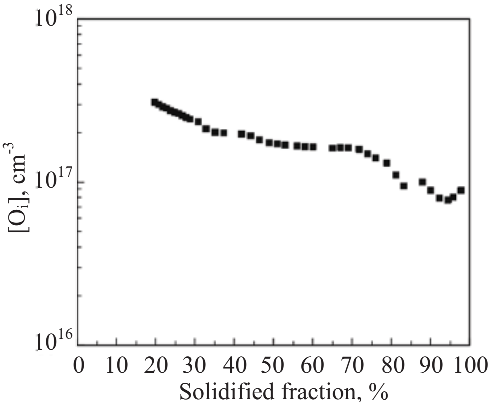


Fig. 10. Change in Oi concentration along the height of a mono-like Si ingot

5. 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 output voltage at a constant temperature (65 °C) and illumination (43 mV, ~1.1 "Sun") every second.

Table 2 shows the results of the LID tests performed. To confirm the stability of measurements, a reference SC without the 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 mono-like Si, which correlates well with the theoretical data on the formation of B-O complexes at an oxygen concentration of $>3\times10^{17}$ cm^{-3}. According to measurements, the concentration of interstitial oxygen [Oi] in mono-like Si (Fig. 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 $\sim8\times10^{17}$ cm^{-3}, silicon grown by the mono-like 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 output voltage, short-circuit current density, FF, η for solar cells made from mono-like Si

SC position along ingot height, %	Relative losses, %			
	Δ output voltage	Δ short-circuit current density	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

The graph below illustrates the light degradation results extracted and expressed in relevance to Fig. 10 demonstrating the dependence between the voltage output and associated outcomes.

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 is reported on the influence of the SC architecture on the degradation effect under illumination [26]; it is shown that SC with a passivated surface are more sensitive to degradation. The obtained LID results have not yet been explained and require further analysis.

6. Discussion of the results of the photovoltaic cells study in terms of efficacy

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, which can form additional energy levels in Eg. As a result, the recombination activity of the cell increases and total efficacy 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 Fig. 9, 11 that for quasi-single-crystal silicon, total efficacy is higher due to the initial high values of total efficacy and initial temperature before removal of impurities (Fig. 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. The values of total efficacy and initial temperature 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 total efficacy and defects. The increase in total efficacy after the removal of impurities is lower for wafers from a side block of quasi-multi-crystalline silicon and all mc-Si wafers (Fig. 7, *a*, *b*). This circumstance suggests that the absence of an increase in the removal of impurities total efficacy may mean that total efficacy depends more on crystallographic defects than on impurity concentrations. 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 is reported on the influence of the SC architecture on the degradation effect under illumination [26]; it is shown that SC with a passivized surface is more sensitive to degradation. The obtained LID results have not yet been explained and require further analysis. Perovskite sunlight powered chargers appear to be the material representing things to come as they can possibly cost not as much as silicon and they are likewise more lightweight. Recent MIT research has consolidated perovskites with silicon cells, making a mixture that is productive and could be less expensive than customary silicon just boards. A few organizations are beginning up to make and sell perovskite-silicon pair cells.

7. Conclusions

1. According to the findings, the presence of a large number of metal impurities can cause formations in the form of deposits in crystal defects or dissolve in silicon, lowering its efficacy when employed in PV solar cells. Similarly, the total efficacy is larger due to the initial high values of total efficacy and initial temperature before impurity elimination for quasi-single-crystal silicon.

Furthermore, fewer sunlight-powered chargers are tested at sequential voltages than others of comparable wattage worth, which determines how much current is available. The increase in total efficacy after the removal of impurities was found to be lower for wafers from a side block of quasi-multi-crystalline silicon and all mc-Si wafers.

2. Based on the results, it is obvious that short-circuit current density and output voltage are higher for solar cells manufactured of quasi-single-crystal silicon due to higher total efficacy values. The short-circuit current density and open-circuit voltage values are highly reliant on total efficacy. The efficiency of mono-like Si plates was slightly higher.

3. The results show that the average value of the relative degradation of the efficiency is ~1 % and there is an insignificant effect of LID on the efficiency of SC made of mono-like Si. Equally, SC with a passivated surface was found to be more sensitive to degradation.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Acknowledgments

It was free of charge due to a partnership with silicon factories and production sites for the assembly of photovoltaic cells in the city of Ust-Kamenogorsk “Kazakhstan Solar Silicon” in Republic of Kazakhstan. This study was conducted at KazPV production sites at plants in Republic of Kazakhstan in the cities of Ushtobe (silicon plant) and Ust-Kamenogorsk (assembly of photovoltaic cells) with the participation of the French industrial company ECM Greentech (France).

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