ISSN 0040-6015, Thermal Engineering, 2011, Vol. 58, No. 11, pp. 932–947. © Pleiades Publishing, Inc., 2011.
Original Russian Text © G.G. Untila, M.B. Zaks, 2011, published in Teploenergetika.

Silicon-Based Photovoltaics: State of the Art and Main Lines of Development

G. G. Untila[a] **and M. B. Zaks**[b]

[a]*Skobel'tsyn Research Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b]*Solnechnyi Veter (Solar Wind) Firm, ul. Tamanskaya 180, Krasnodar, 350040 Russia*

Abstract—Lines of scientific and technical research works carried out in the field of silicon solar cells and aimed at reducing the cost of photovoltaic power, which is the fundamental problem of photovoltaics, are considered. Main results obtained by specialists of the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter (Solar Wind) Firm are presented.

DOI: 10.1134/S0040601511110139

Solar radiation is one of environmentally clean renewable sources of energy viewed as a possible way in which countries and regions lacking their own resources of traditional kinds of fuel can solve the growing problems of ensuring energy security and environmental safety already in the foreseeable future [1]. The amounts in which solar energy arrives to the earth surface are almost unlimited, they are available everywhere, they are many times greater than the foreseeable demands of the mankind in energy, and they are continuously replenished.

Solar radiation features high quality from the viewpoint of thermodynamics: theoretically, it can be converted with high efficiency into electric energy and heat required for a human. As regards heat, it can be obtained with almost any temperature potential (theoretically, to almost the Sun's radiating surface temperature equal to 6000 K). Owing to this fact, it is in principle possible to convert solar energy into electric energy with high efficiency both directly (in solar cells) and via thermodynamic cycles (with the use of radiation concentrators and thermal cycles).

Unfortunately, solar radiation as primary source of energy has some essential drawbacks: its flow has rather low power density (up to 1000 W/m^2 in clear noon and up to 250 W/m^2 on the average a year in the sunniest regions on the globe); besides this, solar radiation arriving to the earth surface features seasonal and daily variations and depends on the weather. Thus, in making large-capacity solar power installations, solar radiation receivers of a large surface area need to be constructed, which entails relatively high costs for equipment and results in that such devices are less competitive as compared with more compact traditional fossil-fueled power installations, the power flows in which have densities of several hundred kilowatt per square meter. Clearly, solar power installations can be made more competitive, first, by increasing their efficiency (due to which a smaller required surface area of the cells is achieved) and, second, by reducing their specific cost per unit surface area of the receiver.

Photovoltaics is the most rapidly developing sector of solar power engineering. This can be seen from the following figures. The amounts by which power installations other than solar ones, as well as the production of alternative fuels, increased in 2009 were as follows: wind power, 32%; thermal power (water heating), 21%; geothermal power, 4%; hydraulic power, 3%; and production of ethanol and biodiesel, 10 and 9%. As regards solar cells (SCs), the amounts of their sales in the world's market grew on the average by 60% in 2004–2009 (Fig. 1), by 66% in 2009, and by 74% in 2010. The overall capacity of SCs produced in 2010 totaled 20.5 GW$_{peak}$ [2], of which 18.2 GW$_{peak}$ were commissioned, and the overall capacity of the installed photovoltaic (PV) systems reached almost 43 GW$_{peak}$. For comparison, the overall capacity of SCs produced and commissioned in 2009 totaled 11.8 and 7.6 GW$_{peak}$ and grew by 74 and 139%, respectively.

In 2009, the annual production of electric energy totaled 23.9 trillion kW h. The average cost of 1 W$_{peak}$

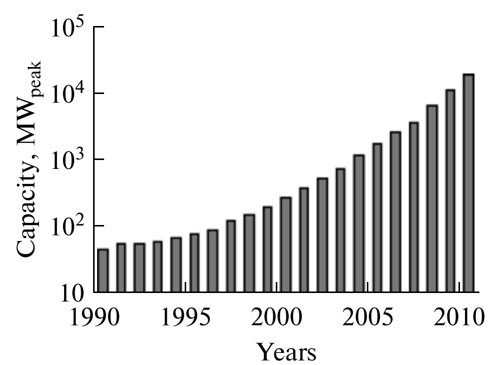

Fig. 1. Annual amounts of SCs produced in the world.

Table 1. Some parameters of photovoltaics in 2009

Country	Installed capacity, MW_{peak}	Produced, MW_{peak}	Budget of R&D works, $million	Cost* of PV system, $\$/W_{peak}$	Tariff**, cent/(kW h)
Australia	183.7	12	9.8	4.7–7.8	10.2–15.6
Austria	52.6	7.5		5.3–7.6	26.4
Belgium	363	–	–	–	–
United Kingdom	29.6	–	–	8.1–8.7	–
Germany	9845.0	2456	73.5	3.9–5.3	31.5
Denmark	4.6	–	4.7	3.7–9.3	37.5
Israel	24.5	–	0.5	3.6–5.9	12.5
Spain	3523.0	23		4.2–5.9	
Italy	1181.3	66.1	6.9	4.2–6.3	23.6
Canada	94.6	0.3	3.2	–	6.1
China	305.0	3800	–	–	–
Korea	441.9	231	55.4	6.2	13.3–19.6
Malaysia	11.1	780	–	6.2	<13.5
Mexico	25.0	–	0.5	6.5	<36.2
The Netherlands	67.5	–	16.7	–	–
Norway	8.7	180	14.5		11.1–14.3
Portugal	102.2	5.5		5.6–6.9	10.3–19.2
The United States	1641.6	770	145	3.5–5.0	10.4
Taiwan	–	1400	–	–	–
The Philippines	–	400	–	–	–
France	430.0	–	–	3.5–6.3	–
The Czech Republic	411.0	–	–	–	–
Switzerland	73.6	>0.8	–	5.1–6.7	14.7
Sweden	8.8	–	7.6	6.1	18.3–20.9
Japan	2627.2	1487	44.5	5.8	19.1–25.8

Notes: * For PV systems connected via a network with a capacity of higher than 10 kW.
** Feed-in Tariff.

in a solar module (SM) dropped as compared with 2008 by 35% from $\$3.5/W_{peak}$ to $\$2.6/W_{peak}$ and in some cases to $\$2/W_{peak}$ [3]. According to forecasts, this cost will drop by 37–50% a year in the next five years [2], and the cost of 1 W_{peak} in PV systems united by a network dropped by 30% to $\$4.8/W_{peak}$ (it sometimes reached $\$3.5/W_{peak}$ on the average) [3].

China (which accounts for more than 30% of the market), Germany, Japan, and Taiwan are the leaders in production of SCs (in 2009) (Table 1), whereas the countries occupying leading positions in purchasing PV systems include Germany (9.8 GW_{peak}), Spain (3.5 GW_{peak}, of which around 3 GW_{peak} was commissioned in 2008), Japan (2.6 GW_{peak}, which was the leader up to 2004), the United States (1.6 GW_{peak}), and Italy (1.2 GW_{peak}; for comparison, the installed capacity of PV systems in 2007 totaled 120 MW_{peak}). If we recalculate these figures per capita, the three leading countries remain the same, but the United States drops to tenth place, whereas Switzerland rises from the fourteenth to the fifth place. With such a boomlike growth of photovoltaics, changes may occur in the list of leaders. For example, India intends to install PV systems with a total capacity of 20 GW_{peak} by 2022 and 100 GW_{peak} by 2030.

It should be pointed out that photovoltaics is actively developed not only in countries with high insolation. For example, the insolation in Germany is at the same level as it is in Moscow, whereas the insolation in the Netherlands, Belgium, United Kingdom, Norway, and Sweden is even lower than in Moscow. The insolation in the south of Russia, in the Magadan oblast, and in the Primorsky krai is at the same level as in Italy and France [4]. Therefore, the fact that Russia does not have any essential PV installations is due to lack of the appropriate political decisions and state grants rather than due to insufficient insolation. The Feed-in Tariff law, which has been adopted in 63

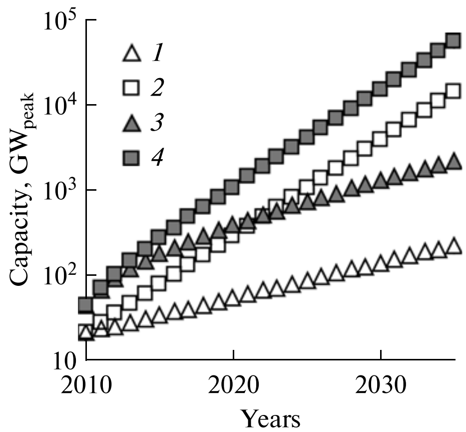

Fig. 2. Forecast of the annual production (*1*), (*2*) and installations (*3*), (*4*) of PV systems for two scenarios: with an annual growth of production equal to 30 (*2*), (*4*) and 10% (*1*), (*3*).

countries, is applied around the world as a political mechanism for stimulating the development of photovoltaics to the parity with power systems. For example, when the Czech Republic, the insolation in which is the same as in Moscow, adopted this law in 2008, the overall capacity of PV installations in it increased by a factor of 9 (to 411 MW_{peak}). The adoption of this law caused the capacities of PV installations to grow by a factor of 19 in Israel, by a factor of 9 in Canada, and by a factor of 2–4 in Austria, Switzerland, and other countries.

COST OF PHOTOELECTRICITY

The main question that is usually of concern for a customer is how much the electricity in a receptacle will cost if a PV system is installed. It is rather difficult to give an exact answer to this question, but a simplified algorithm for making an estimate is as follows [5]. Suppose that we wish to install a PV system with an area of 1 m^2. The following two alternatives are considered: the system has an efficiency equal to 10 or 20%; i.e., its capacity is equal to 100 or 200 W_{peak}. We assume that the system is supposed to be used in locality with insolation equal to 1200 (kW h)/m^2 a year (Moscow, the Czech Republic, and Germany). Then, the PV systems with efficiencies equal to 10 and 20% will produce 120 and 240 kW h a year, respectively, while having the same amount of energy produced per watt of installed capacity, equal to 1.2 (kW h)/W_{peak}. Thus, irrespective of the PV system efficiency, each watt of installed capacity will produce 1.2 kW h a year and 36 kW h for 30 years (such service life is now guaranteed by manufacturers of silicon SMs). Finally, if the PV system was bought at a price of \$3.6/W_{peak}, the cost of 1 kW h of photovoltaic energy will be \$0.1/(kW h). This is the minimal value, because it was determined without taking into account many other factors, such as expenditures for maintenance of the PV system, for land lease, interest for bank credit, profit, etc. Clearly, if insolation is higher (1400–1700 (kW h)/m^2 a year in the Krasnodar krai and 2000 (kW h)/m^2 a year in Spain), the amount of produced energy will increase proportionally, and the cost of photoelectricity will be lower. For a PV system be able to compete with other sources, the cost of photoelectricity must be reduced. It is commonly adopted that \$3/W_{peak} for a PV system (\$1.5/W_{peak} for an SM) is the threshold below which photovoltaics can freely compete with other sources of energy in the market.

Silicon-based semiconductor devices play the leading role among different types of PV systems that are being developed. It is exactly this line of works in the field of photovoltaics the state of the art and prospects for future development of which are discussed in this paper.

IS PHOTOVOLTAICS ABLE TO OCCUPY A NOTICEABLE PLACE IN POWER ENGINEERING OF THE FUTURE?

Let us estimate what power capacity of PV systems is required for producing, say, 1.2 trillion (kW h)/year, i.e., 5% of the amount of electric energy produced presently around the world (by 2010, a total of 4.8 TW_{peak} of power capacities had been installed around the world, which produced approximately 24 trillion (kW h)/year, i.e., around 5 (kW h)/W_{peak}). We assume that all these systems are installed in a locality with insolation equal to around 1400 (kW h)/m^2 a year (Voronezh, Tambov, Penza, Ul'yanovsk, and Ufa). Earlier, it was shown that under these conditions, each installed watt of peak capacity will produce 1.4 kW h a year; hence, approximately 860 GW_{peak} of installed PV capacities, or 5700 km^2 of PV systems with efficiency equal to 15% must be available for producing 1.2 trillion (kW h)/year. Since the service life of a PV system is equal to 30 years, 28.6 GW_{peak} (190 km^2) of PV capacities must be installed every year for maintaining this level (860 GW_{peak}). It should be reminded that 18.2 and 7.5 GW_{peak} were installed in 2010 and 2009, respectively.

What is the expected date by which the amount of electricity produced by PV systems can reach 5% of the present-day consumption of energy? This moment of time can be predicted if we specify certain production growth rates. Of course, there are no grounds to figure that the production of solar cells will grow by 50% every year; this is impossible. Therefore, we will consider two scenarios: with a 30% growth (moderate) and a 10% growth (very moderate).

As is shown in Fig. 2, with the production growth rate equal to 30 (10)%, 1 TW_{peak} of capacities will be installed in 2020 (2028), i.e., quite soon on a historical scale. It is interesting to point out that the commissioning of the present-day 4.8 TW_{peak} of capacities can be expected in 2026 (2043).

A FORECAST OF THE PRICE FOR SOLAR MODULES

The price of 1 W_{peak} in SMs varied in the period from 1979 to 2009 (Fig. 3) according to the classic law, namely, a linear dependence of the price vs. the accumulated amount in the logarithmic coordinates: it dropped by 20% as the amount of installed SMs increased by a factor of 2. Extrapolation shows that the price will drop to $1/$W_{peak}$ when 200 GW_{peak} of capacities are installed. With the growth rate equal to 10%, this will occur already in 2016 (see Fig. 2).

Thus, the potential for development of photovoltaics is so great that it soundly pretends to occupy a noticeable place in power engineering of already the foreseeable future. New approaches should be developed for achieving this goal, the use of which will make it possible to increase the efficiency, decrease the consumption of materials, and reduce the cost of 1 W_{peak} of installed capacity.

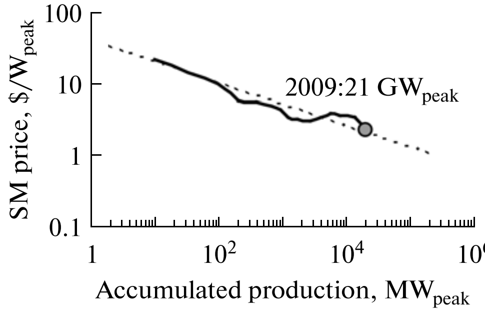

Fig. 3. Reduction of the price of 1 W_{peak} in a solar module with the accumulated amount of SMs.

SILICON AS THE BASIS OF MODERN PHOTOVOLTAICS

Photovoltaics reckons its history from 1954, the year in which a solar cell with an efficiency of 4.5% was obtained at Bell Laboratories (the United States). This cell was made of crystalline silicon (c-Si), material that dominates in the production of SCs still at present.

It follows from Table 2 that in 2008, as in 1999, around 90% of all solar cells were made of multicrystal silicon (mc-Si), ribbon silicon, and single-crystal silicon grown according to Czochralski's method (Cz-Si), and the amount of production had increased for that period of time by a factor of 36.5. Thin-film SMs made of amorphous silicon (a-Si) CdTe and modules made on the basis of a cuprum-indium-selenium alloy (CIS) have been trying to compete with c-Si for already 30 years, but attempts to do so have not hitherto met with success. Apart from being toxic (Cd) and available in limited amounts (Te and In), SMs made of these materials have considerably poorer efficiency. According to forecasts, if the production of SCs made of CdTe increases in scale, the prices for tellurium will rise by a factor of 10–100, and their cost will be no lower than that of silicon cells [5].

Since the amount in which SCs are produced is supposed to be increased further by a factor of 1000, an unlimited source of raw materials for producing them is necessary, which, however, must not pollute the environment. Silicon SCs comply with this requirement; the source material for manufacturing them (quartz) is not only readily accessible but also widely abundant (one-third of the Earth consists of silicon), due to which the danger of monopoly is excluded. A forecast shows that c-Si will continue to dominate in photovoltaics in the medium-term prospect, and there is no alternative to it as yet. Therefore, the European Photovoltaic Power Industry Association (EPIA), which has plans to bring the share of solar electricity to 12% in Europe and to 5% in the world, stakes exactly on silicon-based photovoltaics [6].

THE OUTLINE OF THE MODERN SILICON-BASED PHOTOVOLTAICS

Screen Printed Solar Cell. In 1975, a simple and cheap technology for manufacturing contacts by alloying silicon with metal-containing pastes applied using the screen printing method was developed. The design of a SC called a screen printed solar cell was developed on the basis of this technology (Fig. 4a).

Wafers of *p* type are used. The wafer surface having the orientation (100) is subjected to texturing in a solution of alkali with isopropyl alcohol to reduce reflection loss, as well as for refracting light in order to increase the optical path. A *p-n* junction is formed by diffusion of phosphorus. A film of hydrogenated silicon nitride (a-SiN_x:H) is applied to the face side serves as antireflection coating and at the same time passi-

Table 2. Fraction of semiconductor materials in the production of SCs in 1999 and 2008

Material	Fraction in the total amount of SCs, %	
	1999*	2008**
mc-Si	47.5	49
Cz-Si	39.8	38
Ribbon Si	3.8	1
a-Si	8.3	5
CdTe	0.4	6
CIS	0.2	1

Notes: * Goetzberger A. et al. Mat. Sci & Engnf. 2003. R 40. p. 1–46.
** Hesse K. Proc. 24th EU PVSEC. Hamburg, 2009. p. 883–885.

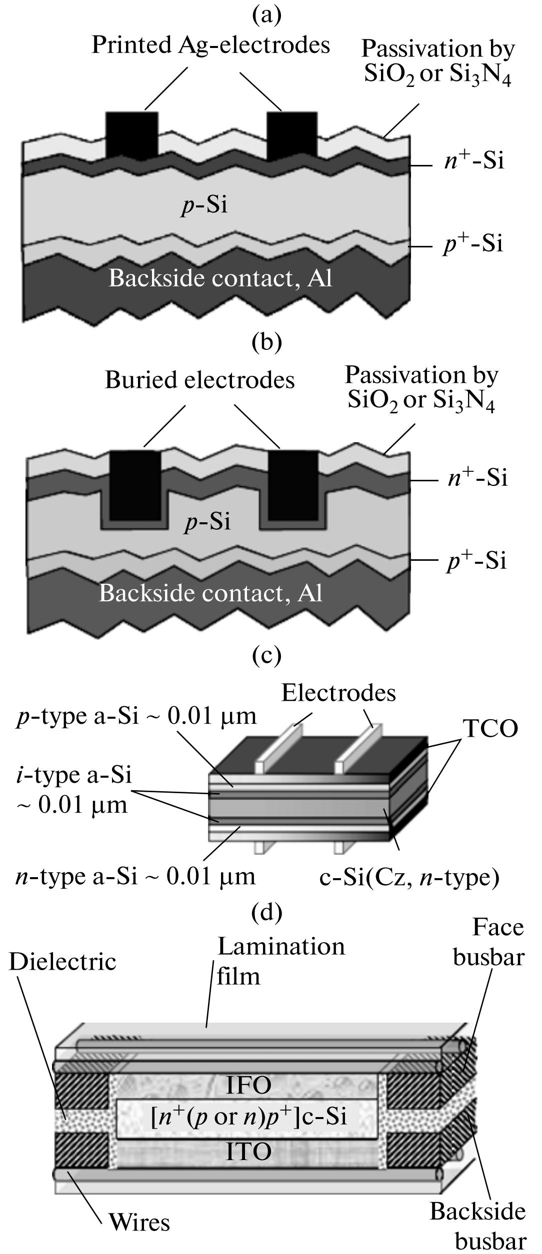

Fig. 4. Designs of solar cells. (a) Screen printing, (b) with buried Saturn contacts produced by BP Solar, (c) with the HIT-structure produced by Sanyo, and (d) Laminated Grid Cell produced by the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter Firm.

vates the surface. After that, contact fingers (CFs) made of silver past are applied to the face side, and a continuous layer of aluminum paste is applied to the back side; the contact fingers and the layer of aluminum paste are fired in at a temperature of above 800°C. Owing to its simplicity and high output, the screen printing technology has remained a commercial standard since the early 1980s and dominates in the industry. However, essential drawbacks inherent in screen printed contacts limit the efficiency of SCs at a level of 14–16%.

SCs with buried contacts. In 1985, a solar cell with (Ni/Cu/Ag) contacts buried in 20-μm wide and 60–100-μm deep grooves made using the laser technology was developed, which was commercialized by BP Solar (England) (Fig. 4b). The efficiency of this SC, called a laser grooved buried contact (LGBC), reaches 18.3%.

High-efficient SCs. In the early 21st century, two designs of high-efficient solar cells emerged in the market. In 1997, the Sanyo Co. (Japan) began to manufacture so-called heterojunction with intrinsic thin-layer (HIT) solar cell on the basis of the a-Si/c-Si heterojunction (Fig. 4c), and in 2003, the SunPower Co. (the United States) began to manufacture so-called interdigitated back contact (IBC) solar cells with backside opposite-comb contacts. These SCs had efficiencies equal to 23 and 22%, respectively. However, the designs of HIT and IBC solar cells require expensive silicon with the lifetime of carriers more than 1 ms, i.e., by more than an order of magnitude longer than in the bulk of routine c-Si wafers.

PURPOSES AND OBJECTIVES OF PHOTOVOLTAICS: THE EPIA ROAD MAP

Photovoltaics is viewed as power engineering of the 21st century able to make serious contribution in the supply of energy to the mankind. To this end, the task is set forth to increase the amount of production by around a factor of 1000 and reduce the cost of photovoltaic electricity. What ways have been contemplated for achieving this? In 2004, the EPIA formulated the objectives of the further development of silicon photovoltaics in its road map up to 2010 (2020). The main of these objectives are as follows [6]: to reduce the consumption of c-Si from 16 to 10 g/W_{peak} (8 g/W_{peak}), to reduce the thickness of silicon plates from 300 to 180 μm (160 μm), to increase the efficiency of SCs made of Cz-Si from 16.5 to 20% (22%), to increase the efficiency of SCs made of mc-Si from 14.5 to 17% (19%), and to develop high-efficient contacts.

HIGH-EFFICIENT CONTACTS

Electrical contacts determine the "face" of a solar cell both in literal and figurative senses. High-efficient metallization must allow the following parameters to be minimized: the width of contact fingers, the longitudinal resistance of CFs, the area of the contact with silicon, and the resistance of the contact to emitters with low surface concentration. In addition, the emitter must not be shunted; the process must go at low temperature in order to keep the passivating films made, e.g., of a-Si, from degradation; and finally, the process must not exert mechanical pressures for the possibility of applying it for thin c-Si wafers. Contacts evaporated in vacuum comply with these requirements; however, they are not acceptable for the manufacture of SCs. Screen printing is a simple and cheap process, due to which it has still been dominating in the production; however, it has essential drawbacks: the CFs have a large width (approximately 125 μm) and moderate conductivity (0.24–0.4 Ω/cm), the metal/Si contact has considerable resistance (around 5 mΩ cm^2), the CFs are characterized by a low aspect ratio, mechanical pressure is exerted during the printing process, high-temperature annealing (800–900°C) has to be used, and the technology can be applied only for heavily doped emitters with a sheet resistance of approximately 40 Ω/sq.

Plating. The approach used in LGBC solar cells, the idea of which is to precipitate metal in windows opened in the dielectric film of antireflection coating, has recently been actively developed as an alternative to the screen printing method. Various methods for opening windows and shaping the metallization pattern are investigated, including laser-assisted shaping of grooves, laser ablation of dielectric, laser ablation of resist, application of resist using a jet printer followed by chemical etching, and printing of etching pastes. As a rule, nickel is first deposited into the windows using a chemical method followed by thermal treatment, after which galvanic or light-induced electric deposition of metal is carried out. As a result, the possibility of making 50–60-μm wide CFs with a contact resistance of less than 1 mΩ cm^2 was demonstrated. Solar cells made of Fz-Si and Cz-Si with efficiencies equal to 20.7% and 17%, respectively, have been obtained.

Laser fired contacts. A process for making high-efficient metallization for the back side of monofacial SCs has been developed at Fraunhofer ISE (Germany). This process, called the technology of laser fired contacts (LFC), consists in the following: a passivating SiO_2 or SiN_x film and a layer of aluminum are applied on the SC back surface, after which the aluminum layer is locally heated using a Nd:YAG laser due to which the passivating film is burnt and a local p^+ layer is formed with the Al/p^+-Si contact having a specific resistance of 0.3–1 mΩ cm^2. Aluminum is deposited by thermal vacuum evaporating (for which special high-output equipment is developed), as well as using the screen printing method, and even in the form of foil. Solar cells with efficiency higher than 20% have been obtained.

Ink-jet printing of contacts. In recent years, use of jet printers in the manufacture of SCs has intensely been studied, also for printing contacts with special metal-containing ink made using nanoparticles of silver. A nucleating layer of silver is applied on the antireflection coating (SiN_x), and a contact is formed by high-temperature firing (at 880°C) in a way similar to the screen printing process, after which silver is grown by electroplating, due to which the fingers become wider. Contact fingers with a width of around 45 μm and having the aspect ratio equal to 1/3–1/5 have been obtained. Unlike the screen printing technology, this method does not exert mechanical pressure on the SC, and the contact fingers obtained using this method are thinner and have lower specific resistance. The drawbacks of this method are that it gives large contact resistance (5–8 mΩ cm^2) and that the process has to be carried out at high temperatures.

Laser grooved buried contacts. In the initial LGBC technology, nickel was chemically deposited into grooves made using the laser method, and the contact was grown by electroplating. For making the process cheaper, a hybrid version was developed within the framework of the Lab2Line project of the FP6 program, in which CFs are applied into grooves but using the screen printing method. The efficiency equal to 17.5% has been obtained.

Films of transparent conducting oxides (TCO). The idea of introducing TCO films into the design of a SC made of c-Si with a *p-n* junction as a transparent electrode and simultaneously as antireflection coating has long been attracting attention due to its great potential. However, TCO films are not used in the manufacture of "standard" SCs, because they are incompatible with screen printed contacts due to their becoming degraded during high-temperature annealing. Specialists of Sanyo have succeeded in solving the problem of making contacts to the TCO film in the HIT solar cells, which are presently the only and the most efficient commercially available type of SCs made of c-Si. Intense efforts are being taken to repeat the success achieved by Sanyo, and different consortiums are being created to this end in Germany, France, and other countries. Since Sanyo produces SCs made of *n*-Si, HIT-type solar cells made of *p*-Si were initially developed, but the efficiency that had been achieved with this material by 2008 was as low as 18.4%, and that with *n*-Si, 19.8% (HMI, Berlin). In recent years, the Roth&Rau Co. has actively joined to the development of this line and, working in cooperation with EPFL (Neuchatel), it achieved the efficiency equal to 21% for a SC with a size of 4 cm^2 and 19.3% for a solar cells with an area of 148 cm^2 in 2010. Poorer efficiency of the SC of a larger size is due to problems with contacts. Attempts to develop high-efficient contacts to TCO are taken, as a rule, with the use of low-temperature pastes.

The LGCell design and its advantages. Specialists of the Moscow State University's Institute of Nuclear Physics and the Solnechnyi Veter (Solar Wind) Firm (SINP MSU & SV) develop a new low-temperature method for making high-efficient contacts called a laminated grid cell (LGCell) [8] for SCs with TCO films. In this case, the method involves two processes (Fig. 4d): application of a film of transparent conducting metal oxide (TCO) and formation of a contact comb of a wire coated by a contact composition attached to the TCO surface using the low-tempera-

Table 3. Parameters of SCs made using the LGCell and screen printing methods

Parameter	LGCell	Screen printing
W, μm	60	125
W^*, μm	~42	125
R_L, mΩ/cm	54	400–1300
R_C, mΩ cm^2	<0.8	5–15
R_{SH}, Ω/sq	Emitter + TCO 30–50	Emitter 40–60
Shunting	No	Yes
Temperature, °C	~150	800–900

Note: W is the width of contact fingers (CFs), W^* is the effective width of CFs, R_L is the longitudinal resistance of CFs, R_C is the contact resistance, and R_{SH} is the sheet resistance between the CFs.

ture lamination method, also with the use of transparent conducting polymer; the current collecting busbars are located near the SC. If the contact to the back side is made using the screen printing method, a contact to the metal is organized on the back side of the wire. The LGCell technology has a few essential advantages as compared with other metallization methods:

—Contact fingers can be made of a very thin copper wire, the effective width D_{eff} of a CF finger made of round wire is a factor of $\sqrt{2}$ smaller than the diameter D (with $D = 60$ μm, $D_{\text{eff}} = 42$ μm).

—Owing to the aspect ratio equal to around unity and the specific resistance of the metal, it becomes possible to obtain the minimal possible longitudinal resistance of CFs (54 mΩ/cm for $D = 60$ μm).

—The resistance of the CF/TCO contact is less than 1 mΩ cm^2.

—In the LGCell there is no need to form a selective emitter, because the TCO film forms a contact to the emitter over the entire surface area.

—In the LGCell it is possible to use a high-efficient homogeneous emitter (with a sheet resistance of higher than 100 Ω/sq), because the sheet resistance of TCO is around 40 Ω/sq.

—The LGCell contact fingers are uniform and have no breaks, which is an essential problem for other technologies, which aggravates as the CF width becomes narrower.

—A unique feature of an LGCell solar cell is that the current collecting busbars in it are located near the SC, which is more preferable than making them on the back side (the developers of the back-contact-solar-cell line strive to do so), which makes it possible to exclude not only shading from the busbars, but also damaging the SC by soldering when the cells are connected in series in a module.

—Cracks that may emerge in an LGCell photovoltaic converter do not lead to a break in the CFs; therefore, the efficiency degrades to the minimal extent, a feature that is especially important during operation of an SM.

—The symmetrical contact system and the fact that the technology for soldering the LGCell busbars does not involve the effect of a soldering iron are especially useful in the case of using thin SCs.

—Shunting of the emitter in an LGCell is excluded owing to a suitable choice of TCO, whereas in the case of using electroplated contacts this problem arises during the nickel annealing process.

Table 3 gives a comparison between the parameters of LGCell contacts and those obtained using the screen printing method. It can be seen that the parameters of LGCell contacts are considerably superior to those of contacts obtained using the screen printing method and are at least as good as the parameters of contacts obtained using other more intricate methods.

The TCO selection principle. In developing the LGCell design, we formulated and experimentally confirmed the fundamental principles of adequately selecting TCO films for use as transparent electrodes to n^+-Si and p^+-Si emitters. In particular, a TCO film must form a barrier contact to the base; i.e., the film used on an n^+-Si (p^+-Si) emitter must create a barrier contact TCO/p-Si (TCO/n-Si). This requirement is extremely important, because high surface conductivity, which is the advantage of TCO, may lead to the emitter becoming shunted through holes, i.e., through regions without diffusion, which appear due to imperfectness of the diffusion process (for HIT TCO/a-Si/c-Si solar cells these are holes in the film of amorphous silicon). The risk of shunting becomes several times higher in the case of using a high-efficient shallow emitter.

It should be pointed out that the range of TCO films used in the industry is quite narrow and includes the most popular tin-doped indium oxide (ITO), fluorine-doped tin oxide (TO), and zinc oxide films doped with indium, aluminum, gallium, etc. According to the TCO selection rule, all of them are applicable only for a p^+-Si surface because they form a barrier contact to n-Si (the SCs obtained from different structures have the following efficiencies: ITO/n-Si, 16.2%; ZnO/n-Si, 8.5%; and TO/n-Si, 12.3%).

Thus, none of all widely known TCO films is suitable for being used as an electrode to an n^+-Si surface. Figure 5 illustrates how the faulted (n^+pp^+)Si structure became shunted due to application of ITO. Therefore, since numerous attempts to introduce TCO films into the design of a silicon SC were based exactly on using the ITO/(n^+pp^+)Si structure, they were doomed to obtain a negative result. It should also be noted that ITO is used in the HIT structure, but the solar cell is just made of n-Si, and, possibly, the use of ITO or ZnO in designing HIT SCs made of p-Si is one of factors due to which they have poorer efficiency.

The only TCO film that forms a barrier contact to p-Si was developed at the Moscow State University's Institute of Nuclear Physics. This is a film made of fluorine-doped indium oxide (IFO) [9]. The obtained SC with the IFO/p-Si structure had efficiency equal to 17.8%, which is a record for SCs made on the basis of a TCO/Si heterojunction. Application of IFO on an n^+-Si emitter with "holes" does not degrade but improves the parameters of the (n^+pp^+)Si structure (see Fig. 5).

An LGCell made on the basis of the IFO/(n^+pp^+)Cz-Si structure obtained by diffusion of phosphorus and boron showed the efficiency equal to 19.2%. For comparison, in 2008, the efficiency equal to 19.1% obtained for a SC with contacts made by means of the screen printing method but using float zone (Fz) silicon was claimed as a record one [10]. Screen printed contacts are considerably inferior to LGCell contacts, and the efficiency equal to 19.1% was obtained exclusively owing to the use of Float zone silicon.

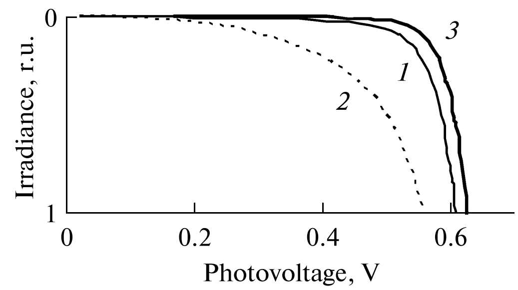

Fig. 5. Irradiance U_{oc} curves for three structures. (*1*)—(n^+pp^+)Si, (*2*)—ITO/(n^+pp^+)Si, and (*3*)—IFO/(n^+pp^+)Si.

A SELECTIVE EMITTER

A highly doped deep emitter with sheet resistance equal to 10–20 Ω/sq is required for obtaining a low-resistance contact with the minimal risk of being shunted. Emitters with sheet resistance of no less than 100 Ω/sq are high-efficient ones. Therefore, a compromise homogeneous emitter with resistance equal to 40–50 Ω/sq is used in standard SCs. In a selective emitter, it is possible to separately optimize the metallized and nonmetallized regions. A few technologies have been actively developed in recent years. It should be pointed out once again that SCs with transparent electrodes made of TCO films (HIT and LGCell) do not require a selective emitter.

Silicon ink. The Innovalight Co. (the United States) has developed a technology on the basis of "ink" prepared from silicon nanoparticles highly doped with phosphorus, which are applied using the screen printing method prior to diffuse phosphorus only on the places where the contacts will be located. After completing the diffusion of phosphorus, sheet resistances equal to 30–50 Ω/sq are obtained in the highly doped region and 80–100 Ω/sq in the lightly doped region. Solar cells with efficiencies equal to 19% made of Cz-Si and 17% made of mc-Si have been obtained.

A SiO_2 mask. A method based on slowing down the diffusion of phosphorus by a mask made of SiO_2 has been developed by the Centrotherm Co. (Germany). Silicon dioxide is structured by subjecting the regions in which contacts will be formed to laser ablation. Laser-induced flaws are etched by chemical methods. Highly doped regions (with a width of 30 μm with sheet resistances equal to 10–20 and 110 Ω/sq in the masked region are obtained. Efficiencies equal to 18.6% have been obtained for a SC made of Cz-Si and 17.1% for a converter made of mc-Si.

The etch back process. This process, which has been developed at the Konstanz University (Germany), is based on applying a mask using the screen printing method or using an ink-jet printer in the locations on a heavily doped emitter at which the contacts will be made, after which the dead layer is subjected to etching by forming porous Si, due to which a few tens of nanometers of thickness are removed in a controlled manner. Efficiency equal to 19% has been obtained.

Ion implantation carried out in two stages (over the entire surface and through a mask) was proposed by the Varian Co. (the United States). The advantages of this approach are that the method is "dry" in nature, no phosphosilicate glass (PSG) is produced, which must be removed afterwards, and there is no need to insulate the edges because the emitter is formed only on the face side. Solar cells with efficiency equal to 18.5% have been obtained.

Laser-assisted doping from PSG. Specialists of the Stuttgart University proposed to use the PSG layer formed after carrying out gas diffusion of phosphorus and obtaining a homogeneous emitter with sheet resistance equal to 110 Ω/sq as a source of phosphorus during the subsequent laser-assisted diffusion of the regions under the contacts. The Manz Co. (Germany) has commercialized the technology. The Centrotherm Co. develops a similar approach, and a SC with efficiency equal to 18.6% has been obtained.

The laser chemical processing method (LCP) for carrying out selective doping was worked out at Fraunhofer ISE, and the RENA Co. (Germany) is actively developing this method. The method is based on subjecting the PECVD SiN_x layer to ablation with simultaneously melting the underlying emitter layer (with sheet resistance equal to around 120 Ω/sq) by means of a laser beam directed by a jet of liquid containing atoms of phosphorus, due to which a high degree of doping is achieved after the molten Si becomes recrystallized. The use of this process makes it possible to form self-aligned contacts by light-induced deposition of NiAg. Efficiencies equal to 19% have been obtained for a SC made of Cz-Si and 16.5% for a cell made of mc-Si.

Laser-assisted doping through SiN_x:H is being developed at UNSW (Australia). After forming a homogeneous emitter with sheet resistance equal to 100–120 Ω/sq and a SiN_x:H layer, selective-laser-assisted doping is carried out, e.g., from the applied phosphoric acid. Windows are opened in SiN_x:H during this process, due to which it becomes possible to form self-aligned contacts by electrically depositing Ni/Cu/Ag. The efficiency of SCs made of Cz-Si is up to 19%. The technology is commercialized by Roth&Rau.

Above, some of the main methods for obtaining a selective emitter were considered. All of them made it possible to obtain SCs with efficiencies up to 19%, which is by 0.6% higher than in cells with a homogeneous emitter. However, none of these methods has gained the status of a commercial standard as yet. The number of additional operations required for implementing each of the methods is the criterion for comparing them, because it has been commonly adopted that the efficiency must increase by at least 0.2% (abs.) per each additional operation.

A SHIFT FROM *p*-Si TO *n*-Si: IS THE PHOTOVOLTAICS ON THE VERGE OF RADICAL CHANGES?

Use of *n*-type silicon for making SCs is more preferable than *p*-type silicon doped with boron for two reasons: first, *n*-Si is less sensitive to usual impurities (e.g., Fe) and flaws than *p*-Si, due to which the lifetime of carriers in it is longer and, accordingly, the maximal SC efficiency is higher, and second, SCs made of *n*-Si are stable, whereas cells made of *p*-Si doped with boron are susceptible to light-induced degradation (LID) connected with formation of boron–oxygen complexes under the effect of light, and their efficiency drops by approximately 1% (abs) as time passes. To overcome the LID problem, it has been recognized that a shift has to be made for using either *p*-Si doped with Ga or *n*-Si. Works with Ga have not received development, but works on constructing SCs made of *n*-Si have become a top-priority line. Two concepts of SCs are being studied: with the *p*-*n* junction on the back side and on the front side.

SCs made of *n*-Si with the junction on the back side. Naturally, the manufacturers began to integrate *n*-Si into the screen printing technology; namely, they began to obtain a p^+ emitter by alloying silicon with aluminum paste. In this case, the *p*-*n* junction is on the back side, and the p^+ surface is not passivated. For achieving higher efficiency, the p^+ surface had to be passivated; therefore, the manufacturers began to remove the layer of paste, make the p^+ emitter thinner by etching, and passivate it. A selective n^+ layer was also used to form an isotype barrier of the front surface, the so-called front surface field (FSF). Table 4 demonstrates the level of the obtained results. The main drawback of this concept of SCs made of *n*-Si is that their efficiency is very sensitive to the quality of silicon, because the *p*-*n* junction is on the back side.

SCs made of *n*-Si with the junction on the front side. Diffusion of boron is another way in which a p^+ emitter can be obtained. In this connection, we should point out the priority of the Russian companies Kvark and Solnechnyi Veter (Solar Wind) (Krasnodar), which developed SCs with a boric p^+ layer as far back as the 1990s and were the first who began to produce bifacial devices made of both *p*-Si and *n*-Si. Although these cells had rather moderate efficiency (around 16%) due to a weakly passivated boron p^+ emitter, it is the Russian companies that pioneered the use of boron diffusion in the manufacture of SCs. Abroad Russia, the Shell Solar Co. (Germany) took one of the first attempts to develop a SC made of *n*-Si with a boron emitter only in 2005, as a result of which a monofacial cells with efficiency equal to 14% was produced by the screen printing method. The results of the developments are summarized in Table 4.

It should be reminded that high-efficient industry-grade SCs (produced by Sanyo and SunPower) are also made of *n*-Si; however, the specific features of their designs imply the use of exclusively high-quality silicon.

Thus, efforts are being taken in the photovoltaic industry to make a radical shift for using *n*-Si with p^+ emitters obtained both by alloying silicon with aluminum and by diffusion of boron. In all likelihood, special aluminum pastes will have to be developed for the first approach. It should be pointed out that the use of *n*-Si was also retarded due to the fact that attempts to efficiently passivate *p*-Si- and p^+-Si surfaces were not met with success. It is only in a few recent years that positive results have been obtained with using films of aluminum oxide Al_2O_3.

DEVELOPMENT OF INDUSTRIAL TECHNOLOGY FOR PASSIVATING BOTH *p* AND p^+-Si SURFACES

The passivating films developed for n^+-type emitters (e.g., a SiO_2 film is the most efficient one of them) do not show equally good performance on a p^+ surface. This is due to the fact that boron has high solubility in SiO_2 taken in combination with the existence in SiO_2 of small built-in positive charge. In addition, the intricate technology used for carrying out passivation and the high temperature required to obtain SiO_2 result in that this material is unattractive for the industry. The second passivating film for an n^+-Si surface that is widely used in the manufacture of SCs, namely, a-SiN_x:H, does not passivate the p^+-Si surface due to large built-in positive charge. The a-Si:H and a-SiC:H

Table 4. Solar cells made of *n*-Si

Organization	Efficiency, %	Details
	Backside alloyed *p*-*n* junction	
Fraunhofer ISE	20.1	Fz 4 cm^2 $p^+/Al_2O_3/SiO_x$
	19.0*	Fz 4 cm^2
Fraunhofer ISE, Bosch Solar	18.6*	Fz 125 × 125 mm
	18.5*	Cz 125 × 125 mm
ISFH, Centroterm, Solland Solar, Ferro	19.8	Fz 4 cm^2, FSP, $p^+/Al_2O_3/SiN_x$
	18.0*	Cz 100 cm^2, FSF
Konstanz University	17.7*	Cz 6"
	18.5*	Cz6" selective FSF
ECN Solar	17.4*	Fz 140 cm^2
ISC Konstanz, Isofoton Hitachi Chemical	17.0*	Cz 156 × 156 mm selective FSF
INES-CEA	17.7*	Cz 148 cm^2 selective FSF
	p-*n* junction obtained by diffusion of boron	
Fraunhofer ISE, Eindhoven University	23.4	Fz 4 cm^2
Fraunhofer ISE	19.6	Fz 140.5 cm^2
CEA, LITEN, INES	18.4	Fz 148.6 cm^2
ECN, Yingli Solar	18.65	Cz 239 cm^2
Moscow State University and Solnechnyi Veter	17.7/13.2	Cz 20 cm^2, bifacial

* Without passivation of the p^+ surface.

films feature considerable absorption in the visible region of the solar spectrum and are thermally unstable; therefore, only low-temperature processes can be used after applying these films.

An Al_2O_3 film is presently the only candidate for the role of an efficient passivator of a p^+-Si surface. Thus, a transparent film with negative built-in charge is required for passivating the p^+-Si emitter. Aluminum oxide Al_2O_3 is the only film among the known ones that satisfies these requirements. The lowest surface recombination rate up to 2 cm/s per 2 Ω cm in Fz *p*-Si is achieved using the method of plasma-assisted atomic layer deposition (PA-ALD). The Al_2O_3 PA-ALD films have successfully been applied for laboratory-grade SCs: efficiency equal to 20.6% has been obtained with Fz *p*-Si, as well as the record efficiency for a converter made of *n*-Si equal to 23.4% (2009). However, the ALD method is characterized by a low film growth rate (around 1.5 nm/min), due to which its use in production is doubtful. Therefore, efforts are presently focused at studying other, more productive methods, e.g., plasma enhanced chemical vapor deposition (PECVD), atmospheric pressure CVD, sol-gel, and evaporating.

In 2010, specialists of the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter Firm used a simple and cheap method of spray pyrolysis for this purpose for the first time and obtained results at the level of the world's best achievements commensurable with the PA-ALD method.

REDUCING THE FRACTION OF SILICON IN THE COST OF SOLAR CELLS

Reducing the expenditure of silicon, also by making SCs thinner, is a top-priority objective of the EPIA. This is because silicon plates account for more than 50% in the cost of solar modules: 31% for crystallization, 24% for plate cutting, 12% for manufacturing the cell, and 33% for manufacturing the SM [these data relate for large-scale production of SMs (500 MW_{peak}/year) made of mc-Si; this fraction will be still higher for SMs made of Cz-Si].

Three approaches to solution of this problem can be pointed out. The first approach, which can be called an evolutionary one, consists in gradually thinning "traditional" SCs to the technological limit (160, 120, and 60 μm). The second approach, which can be called a radical one, implies construction of SCs on the basis of a thin (20–50 μm) layer of high-quality silicon grown on a cheap substrate made, e.g., of low-grade silicon. This design was called crystalline silicon thin film solar cells (cSiTF). Finally, the third approach, called a revolutionary one, presumes manufacturing high-efficient SCs of low-grade silicon; various versions of this approach are based on the idea of a penetrating emitter. Below, these approaches are considered.

Table 5. SCs with the cSiTF structure with contacts made using the LGCell, ECO, and screen printing methods

Contacts	Fraunhofer ISE		Moscow State University & Solnechnyi Veter, EPIEL
	ECO	screen printing	LGCell
J_{sc}, mA/cm^2	29.0	22.9	31.7
U_{irr}, mV	651	615	629
FF, %	79.7	78.1	79.8
R_s, Ω cm^2	0.3–0.7	0.6	0.12
Efficiency, %	15.1	11.7	15.9

Making SCs thinner. Calculations show that by making a SC thinner it is possible not only to preserve its efficiency at the same level, but even to increase it provided that it is furnished with high-efficient contacts and subjected to high-efficient passivation, which is incompatible with the screen printing method. Therefore, new designs and new technologies are required.

The key problem that arises when attempts are taken to make a SC obtained using the screen printing method thinner is that the call may fail as a result of becoming sagged after unsymmetrical metallization is burnt in (the sag may be as large as 5 mm with the critical value for an SM assembly equal to 1.4 mm), as well as after soldering the busbars. For solving this problem, it is proposed to use a symmetrical (face/back) contact comb, to use a low-temperature conducting adhesive for attaching the busbars, and to subject the SC to thermal treatment (cooling to –60°C) to relieve the stresses that arise after the metallization is burnt in.

We cannot but point out the advances made by Sanyo, which obtains nondeformed HIT SCs with a thickness of 85 and even 58 μm. The 98-μm thick SC had efficiency equal to 23.7%, which is 0.7% lower than in "standard" cells (with a thickness of more than 200 μm). These results show quite convincingly the advantage of using low-temperature processes and symmetrical contacts. It should be noted that the use of symmetrical contacts in fact means a shift from the manufacture of monofacial SCs to bifacial ones, which is an additional positive feature. The results obtained for thin bifacial SCs will be considered below.

The cSiTF line. A thin (10–50 μm) high-quality layer of the *p* type or *n* type is applied on a low-grade substrate [which is as a rule of a *p* type and highly doped one (0.005–0.02 Ω cm) (e.g., made of deeply purified metallurgical-grade mc-Si)] using the CVD, epitaxy, or zonal recrystallization methods, after which an n^+ layer is formed by diffusion or also by growing. Table 5 lists the parameters of SCs with the cSiTF structure obtained by Fraungofer ISE using vacuum-evaporated contacts (ECO) and screen printed contacts, as well as the parameters of the cells obtained by specialists of the Moscow State University's Research Institute of Nuclear Physics and Solnechnyi Veter Firm jointly with the EPIEL Firm (Zelenograd), in which the LGCell contacts are used. The LGCell contacts outperformed not only the screen printed contacts, but also the ECO contacts in the value of series resistance R_S: LGCell showed efficiency equal to 15.9% at $C = 1X$ and 17% at 10-x concentration of solar light.

A penetrating emitter. Solar cells made of cheap low-grade silicon using the traditional designs and technologies have moderate efficiency due to a low diffusion length of nonequilibrium carriers. To overcome the problems caused by a low diffusion length, the SC design with a penetrating emitter made in the form of deep parallel vertical grooves was proposed more than 30 years ago. Works carried out in this line became noticeably more active after theoretical calculations, which had demonstrated the advantage of a penetrating emitter over a planar one (the calculation was carried out for a radial *p-n* junction). In practice, deep pores (porous silicon) were, in particular, made by chemical etching, as well as matrices of various 3D structures: pillar, wire, whiskers, and rods using different methods, such as reactive ion etching (Fig. 6a), the vapor-liquid-crystal method (Fig. 6b), laser-assisted texturing (Fig. 6c), and chemical etching (Fig. 6d). No high-efficient solar cells made on the basis of these structures have been obtained as yet; however, the following result should be pointed out: a SC with efficiency equal to 8.7% made on the basis of the structures shown in Fig. 6a has been obtained from silicon doped to 5×10^{18} cm^{-3} with a diffusion length as small as 10 μm (the planar version of the cell had efficiency as low as 4.6%).

BIFACIAL SOLAR CELLS

There is an impression that, when methods of increasing the efficiency and reducing the cost of solar modules made in a monofacial version have been exhausted, the next step is to make a shift to a bifacial SM able to convert into electricity the solar light falling not only onto its front, but also onto its back surface. Indeed, after the thickness of a SC is decreased with a view to increase its front-side efficiency, and passivation and point contacts are used on the back surface, the only thing that remains to do is to open this surface for light to obtain a bifacial SC and additional power output. This regularity can be clearly seen in the works of Sanyo, which, after having reached efficiency equal to 23%, which is the record one for industry-grade SCs, focuses its further efforts on development of four tasks, including elaboration of the HIT Double bifacial module. Sanyo has demonstrated that for the year of observations, the HIT Double solar module generated by 11% more electricity than the monofacial HIT Power solar module due to albedo of the environment. In some cases, this addition may be as much as 50%. Bifacial SCs are partially transparent for infrared radiation; therefore, solar light heats them to a lower extent, and their efficiency degrades to a lesser extent than in a usual monofacial SC.

It should be pointed out that Sanyo and Solnechnyi Veter are the only companies that supply bifacial modules to the market.

The Solnechnyi Veter Firm (Russia) has developed and implemented a technology for small-series production of bifacial SCs made of standard Cz-Si. The cell efficiency is equal to 17–18% when irradiated on the front side and 11–13% when irradiated on the back side. Formally, if proper irradiation on the back side is organized, the energy output from these modules recalculated for the same overall area of an SM will correspond to the energy output from standard monofacial modules with efficiency equal to 25–28%. In our opinion, the bifacial makeup of SCs and SMs may become the deciding advantage in the competition between manufacturers of products for photovoltaic power engineering.

A lot of research projects have been implemented in Europe, the results of which are summarized in Table 6. Since the back side efficiency increases with decreasing the SC thickness, and since bifacial cells have symmetrical (face/back) metallization, which gives rise to smaller stresses, due to which they can be made of very thin silicon plates, thin plates were often used in developments of bifacial SCs, as is seen from Table 6. It should be pointed out that the parameters of the laboratory-grade SCs of the LGCell design obtained at the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter Firm considerably outperform the level achieved in the world for SCs with screen printed contacts and are commensurable with the parameters of cells with vacuum-evaporated contacts (ECO).

Thus, we can state that it is perhaps in the field of bifacial SCs, which is the line in which photovoltaics is unavoidably developed, that the Russian developments outpace and outperform in their parameters the level reached in the world, and it should be noted that these advances have been made not only in industrial production, but also in prospective samples of new more efficient designs of SCs.

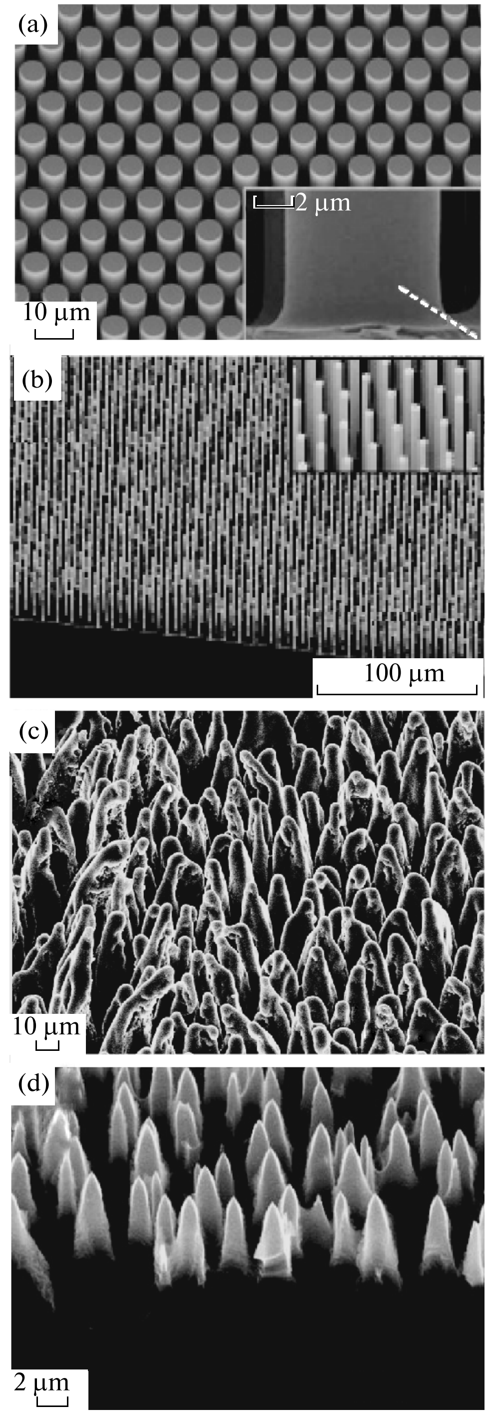

Fig. 6. Matrices of pillar structures. Production methods: (a) reactive ionic etching with photolithography, (b) using the vapor–liquid–crystal method, (c) laser-assisted texturing (developed jointly by the Moscow State University's Research Institute of Nuclear Physics and IPLIT), and (d) photoelectrochemical etching (developed by the Moscow State University's Research Institute of Nuclear Physics).

CONCENTRATOR PHOTOVOLTAICS

The concentrator approach has a large potential for solving the problems of photovoltaics, because the expenditure of silicon decreases in proportion to the degree to which light is concentrated (*C*), and the efficiency can increase due to higher irradiance. The advantage of concentrator systems was demonstrated by carrying out comparative tests under the conditions of the PTS measurement standard, which is maximally close to real operation (AM1.5, 1000 W/m^2, ambient temperature equal to 20°C, and wind velocity

Table 6. Review of the main developments of bifacial SCs made of Cz-Si

Organization (year)	Efficiency, %		Details
	front	back side	
IES-UPM	15.2	17.7	High-resistance n-Si 300 μm, ECO
	14.9	17.0	n-Si 140 μm, ECO
	14.2	14.9	n-Si 240 μm, ECO
	16.0	13.0	p-Si 140 μm, ECO
	13.8	13.7	p-Si 240 μm, ECO
ISFH	14.6	13.0	p-Si 140 μm, screen printing
ISC Konstanz (2010)	17.3	15.0	p-Si 200 μm, screen printing
ISC Konstanz, University of Stuttgart	15.9	14.1	Screen printing, selective B-BSF
ITM, University of Pais Vasco	13.6	11.0	n-Si 120 μm, boron diffusion, screen printing
TiM-EHU, Isofoton, Fraunhofer ISE, CENER, NPC, USF, Ferro	13.0	13.0	n-Si 120 μm, boron diffusion, screen printing
Aachen University, Deutsche Cell, Solland Solar	17.0	10.3	p-Si 200 μm, boron diffusion, SiN_x on the back side
Moscow State University & Solnechnyi Veter	18.1	16.3	p-Si 200 μm, LGCell
	17.7	13.2	n-Si, LGCell

equal to 1 m/s) rather than the unrealistic laboratory standard SRC (AM1.5, 1000 W/m^2, and SC temperature equal to 25°C). It has been obtained that the efficiency of flat-panel modules is in the range 5–12% (PTC), which is essentially lower than the efficiency of laboratory-grade SCs. Only concentrator systems have demonstrated efficiency higher than 20%.

Decreasing the cell's internal series resistance R_S is the key problem of a concentrator solar cell (CSC). If a SC had zero R_S, its efficiency would grow continuously with increasing C. In reality, the dependence of efficiency as a function of C passes a maximum at $C_{opt} = 1/R_S$ [Ω cm^2], after which it rapidly decreases. Therefore, if a CSC is intended to operate in a system with the concentration C_0, the condition $R_S < 1/C_0$ must be satisfied; i.e., the higher the concentration of light, the smaller the value of R_S should be.

Below, three concepts of concentrator photovoltaics are considered: high-concentrator, low-concentrator, and hybrid photovoltaic/thermal ones.

High-concentrator systems. Such systems dominated at the initial stage. Concentrator photoelectric cells were developed using the standard set of methods: contacts fingers were made closer to each other to reduce the fraction of emitter resistance; however, this entailed a growth of shading. Therefore, CFs were made radically thinner by shifting for the use of ECO contacts with photolithography, and a selective emitter was added. As a result, C_{opt} of a CSC became higher, but its cost increased accordingly; therefore, the need arose to decrease R_S still more. To do so, low-resistance Si was used, but the efficiency of a CSC drops considerably if this is Cz-Si; therefore, Fz-Si was taken, which, however, is an order of magnitude more expensive, and the cost of a CSC increases again. There is one else regularity: the higher the concentration for which a CSC is intended, the smaller the size of the device, which entails a stronger adverse effect of the edges, as well as higher labor expenditures per W_{peak}.

The most significant developments of CSCs are given in Table 7, from which it can be seen that the most efficient and highest-concentration CSCs are made of Fz-Si with ECO contacts and photolithography; the LGBC design gives lower efficiency and is designed for lower concentration. However, this is the only industry-grade design using which CSCs made of Cz-Si can be obtained.

Unfortunately, the potential of a high-concentrator SC has not been realized to the full extent as yet, and the state of things is such that in 2008, no commercially available CSCs were available in the market; they were fabricated only for specific projects. Out of more than 20 GW_{peak} of installed PV systems, concentrator systems provide only around 20 MW_{peak}. This is because a balance between the concentration degree and cost of the system has not been obtained. For example, it turned out that the use of high-efficient CSCs (with a efficiency of higher than 26%) in a PV station (Australia) with C = 20–50 X is unprofitable, because they require the concentration C > 100 X. Therefore, stations with higher concentrations began to be constructed, which adds difficulty to the problems of ensuring precise tracking of the Sun and heat removal.

Low-concentrator systems. Recent years have seen a noticeable growth of interest in development of low-concentrator systems with C = (3–5)X made using simple and cheap reflectors and tracking systems, as well as low-concentrator solar modules. Some of these

Table 7. Review of the main developments of concentrator SCs

Organization	Efficiency, %	*C*(X)	Details
Stanford University	27	100	IBC, Fz, a few photolithographies
	26	250	
IES-UPM	21	36	Fz, implantation of boron, photolithography, ECO
	20.7	102	
ANU	22–23	30	Fz, photolithography, ECO, plating
IES-UPM	21	100	Fz, two photolithographies, ECO
	18.5	5	
ANU	20	10–30	Silver, Fz, bifacial
ENEA	18–20	1–100	Fz, photolithography, ECO
Fraunhofer ISE	18.3–19.5	1–15	Fz, MWT (Metal-Wrap-Through)
IES-UPM	21.7	100	LGBC, Fz, best cell
NaREC	19.3	50	LGBC, Fz
	18.7	100	
	19.0	5	LGBC, Cz
	18.2	100	
IES-UPM	14.0–15.5	1–14	Cz, screen printing, plating
Moscow State University, Solnechnyi Veter	18.0–18.5	1–5	Cz, LGCell
	17.7–18.0	1–6	Cz, LGCell, bifacial

systems are designed so that both surfaces of the module are illuminated; therefore, bifacial SMs should preferably be used in them.

Bifacial SMs can be used as conventional ones in power systems of any type (on the roof, in fields of modules, etc.) and in this case they outperform the standard modules with the same efficiency in the energy output. But the advantages of bifacial SMs are realized to the full extent in special designs developed by a few companies, e.g., Poulek Solar (the Czech Republic) and Prism Solar (the United States). Prism Solar has suggested an interesting design of a planar holographic concentrator (3X) for which a Sun tracking system is not required. Prism Solar has carried out comparative energy production tests of different modules, including the most efficient commercially available modules HIP-J54BA2 of Sanyo (η = 17.3%), SPR-215-WHT of Sun Power (η = 19.7%), and modules of its own design furnished with bifacial SCs produced by Solnechnyi Veter (η = 17.2%). A considerable increase in the specific power output in the case of using bifacial SCs was obtained due to a specific design of the Prism Solar module furnished with a planar concentrator which irradiates also the cell's back side. The bifacial SC used in this module (η = 17.2%) is equivalent in energy output to the standard SC with efficiency equal to 21–22%. Appearance of other no less efficient designs for operation with bifacial SCs can also be expected.

Bifacial SMs modules have one else advantage. The results of our studies show that bifacial SCs subjected to intense irradiation are heated to a considerably lower temperature than monoifacial devices, due to which their parameters degrade to a lesser extent. This is also confirmed by the experience gained at Poulek Solar, which has carried out field tests of monofacial and bifacial SMs from one producer at a concentration ratio as low as C = 1.6 X, wind velocity less than 1 m/s, and ambient air temperature equal to 22°C. The working temperature of monofacial SMs was 53°C and that of bifacial ones was by 12°C lower (41°C). As a result, it has been obtained both theoretically and experimentally that the tracking concentrator-type (C = 1.6X) monofacial and bifacial SMs produce energy outputs that are 80% and a factor of 2 greated, respectively, than the standard fixed monofacial SM.

For low-concentrator PV systems cheap CSCs are required; therefore they are now made using SMs either with usual screen printed contacts or with additionally improved by electro-plating growing, which, however, have rather low efficiency equal to 14–15.5% (monofacial ones, with C = 1–14 X). The CSCs of the LGCell design developed at the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter Firm have considerably better parameters: 18–18.5% (C = 1–5 X) for a monofacial CSC and 17.7–18% for a bifacial one (see Table 7). It should be pointed out that the latter result is a unique one because according to the data from the literature, these are the only high-efficient concentrator and at the same time bifacial SCs made of Cz-Si. Bifacial concentrator SCs are not available in the market, and all developments are directed at obtaining a monofacial concentrator-type photovoltaic converter.

Hybrid concentrator photovoltaic/thermal systems. In implementing photothermal systems it is supposed to use solar light for heating a heat carrier (water), possibly, by concentrated solar light. However, hot water does not satisfy all demands of the mankind, for which electricity is required to a larger degree. On the other hand, only 10–18% of the incident solar power is converted into electricity in a silicon SM, and the remaining part of light is uselessly lost as it converts into heat, which causes the SM becoming heated, due to which its efficiency drops. Concentration of light, as was considered above, is useful for making photoelectricity cheaper; however, this results in that the SM is heated and its efficiency drops still more intensely. It is proposed to combine these two lines in hybrid concentrator photovoltaic/thermal (CPVT) systems and use the thermal energy released in the SM module for heating heat carrier, due to which the module will be cooled and its efficiency regenerated. This approach has also received active development in recent years, and an analysis of the last developments can be found in 2010 reviews, e.g., [11, 12].

It is important to emphasize that, as experimental investigations have shown, the hybrid CPVT system equipped with bifacial SMs produced by 40% more electricity than a usual system equipped with monofacial SMs, which is another evidence showing that bifacial solar modules are superior to monofacial ones.

SUBJECTING SOLAR CELLS MADE OF mc-Si TO TEXTURING

It is commonly known that plates made of multicrystalline silicon are cheaper, but the SC made of mc-Si has efficiency lower than that of the cell made of c-Si. Apart from the obvious degradation of their characteristics due to recombination at grain boundaries, there is also the problem of texturing the surface of mc-Si, which stems from the fact that the known surface texturing technologies are either inapplicable or are inefficient for mc-Si. Therefore, new methods are required that will make it possible to decrease reflection of light from a SC made of mc-Si.

Reactive ion etching (RIE) and isotropic acid etching are the main methods for texturing SCs made of mc-Si. However, none of these methods has reached the status of mass production technology, because RIE is an intricate process requiring expensive vacuum equipment, as well as gas supply and entrapping systems, whereas reflection from mc-Si wafers treated in an acid etchaut is no less than 20%. In resent years, active research works have been conducted on micro- and nanostructuring of silicon surface using impulse laser radiation; the researchers who carry out these works often claim the possibility of applying this method to silicon SCs. However, developments of solar cells implementing this approach are extremely few in number, and their results are far from being complete.

Specialists of the Moscow State University's Research Institute of Nuclear Physics and the Solnechnyi Veter Firm, working jointly with specialists of the IPLIT enterprise (Shatura) have obtained a record-breaking low reflection less than 3% (weighed by the solar spectrum in the wavelength range 300–1100 nm) using the developed method of laser-assisted texturing of mc-Si wafers by a matrix of pillar structures (see Fig. 6c). For comparison, the reflection ratios obtained at Fraungofer ISE, UNSW, and the CNRS laboratory are less than 20%, less than 15%, and 6%, respectively.

CONCLUSIONS

(1) The photovoltaic power industry, which firmly demonstrates exceptionally high development rates [the amount of SCs produced in 2010 totaled 20.5 GW_{peak} (their production increased by 74%), and the amount of PV systems installed in 2010 totaled 18.2 GW_{peak} (their commissioning increased by 139%)] and steadily reduces the cost of PV systems, soundly pretends to occupy a noticeable place in power engineering of the future.

(2) Silicon solar modules were and have been the basis of photovoltaic power engineering.

(3) The developments of prospective designs and technologies are focused on simultaneously solving two opposite objectives: increasing the efficiency of a solar module and reducing its cost.

(4) The main lines of studies and developments in the field of silicon photovoltaics can be briefly summarized as follows: a SC must be high-efficient, it must be made of cheap thin silicon plates (preferably multicrystal ones and of the *n*-type), and it must be of concentrator type and bifacial. To achieve this goal, new technologies are being developed: for producing high-efficient contacts, a selective emitter, a p^+ emitter by alloying silicon with aluminum, for passivation (this problem is especially acute for p^+-type surfaces), for texturing multicrystal silicon plates, etc.

(5) Unfortunately, any noticeable production of photovoltaic devices or their installation (in comparison with the scales on which they are used around the world) is lacking in Russia, nor is there a law similar to the Feed-in Tariff. The same dismal situation we have also in the photovoltaic science: the reports presented from Russia at annual European conferences devoted to photovoltaics (one of such conferences held in 2010 included 4540 representatives from 83 countries, who made 1643 presentations) are as a rule limited to those from the Ioffe Physical-Technical Institute (SCs made on the basis of A_3B_5), NPP Kvant, and, finally, the Moscow State University's Research Institute of Nuclear Physics jointly with the Solnechnyi Veter

(Solar Wind) Firm (silicon SCs), which clearly points to insufficient financial support provided for Russian science.

At the same time, it should be pointed out that the level of results obtained from investigations carried out in Russia is at least as high as the level achieved around the world and in some fields even outperforms it.

ACKNOWLEDGMENTS

This work was supported by the Ministry of the Russian Federation for Education and Science (State Contract No. 02.740.11.0055), the leading scientific school NSh-3322.2010.2, and the Russian Foundation for Basic Research (grants nos. 10-08-01171, 11-08-01301, and 11-08-01331).

REFERENCES

1. V. E. Fortov and O. S. Popel', *Russia's Power Engineering in the Modern World* (Intellekt, Dolgoprudnyi, 2011) [in Russian].
2. *Solarbuzz Marketbuzz* 2011 World PV Industry Report Summary, www.solarbuzz.com.
3. *Trends in Photovoltaic Applications. Survey Report of Selected IEA Countries between 1992 and 2009. Report IEA-PVPS T1-19:2010*, www.iea-pvps.org.
4. O. S. Popel', S. E. Frid, Yu. G. Kolomiets, et al., "The Atlas of Solar Energy Resources on the Territory of Russia" (OIVT RAN, Moscow, 2010) [in Russian].
5. A. A. Rockett, "The Future of Energy—Photovoltaics," Curr. Opin. in Solid St. Mat. Sci. **14**, 117–122 (2010).
6. G. P. Willeke, "The Crystalline Silicon Solar Cell—History, Achievements, and Perspectives," in *Proceedings of the 19th EU PVSEC, Paris, 2004*, pp. 1–4.
7. V. Avrutin, N. Izyumskaya, and H. Morkoc, "Semiconductor Solar Cells: Recent Progress in Terrestrial Applications," Superlat. Microstruct. **11**, 337–364 (2011).
8. G. G. Untila, T. N. Kost, A. B. Chebotareva, et al., "A New Type of High-Efficiency Bifacial Silicon Solar Cell with External Busbars and a Current-Collecting Wire Grid," Semiconductors, No. 39, 1346–1351 (2005).
9. G. G. Untila, T. N. Kost, and A. B. Chebotareva, "Fluorine Doped Indium Oxide Films for Silicon Solar Cells," Thin Solid Films **518**, 1345–1349 (2009).
10. A. Das, D. S. Kim, V. Meemongkolkiat, and A. Rohatgi, "19% Efficient Screen-Printed Cells Using a Passivated Transparent Boron Back Surface Field," in *Proceedings of the 33rd Photovoltaic Specialized Conference, San Diego, CA, 2008, 978-1-4244-1641-7.*
11. M. Arif Hasan and K. Sumathy, "Photovoltaic Thermal Module Concepts and Their Performance Analysis: A Review," Renew. Sust. Energy Rev. **14**, 1845–1859 (2010).
12. T. T. Chow, "A Review on Photovoltaic/Thermal Hybrid Solar Technology," Applied Energy **87**, 365–379 (2010).