Photoelectric Converters: Current State Analysis and Prospects of Evolution

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***Abstract* – This review provides the analysis of current state and prospects of evolution of photoelectric converters (PEC). There are shown the directions, ways and means of PEC research and development. It is discussed the state of research in Ukraine and industrialized countries, given the forecast of changes in the efficiency of converting solar energy into electricity as well as the cost of industrial production of solar cells. It is shown the comparative characteristic properties of amorphous and nanocrystalline silicon solar cells. The recommendations about promising areas of research and development to improve the efficiency of solar cells are included.**

***Index Terms* – nanocrystalline silicon, nanomaterials, photoelectric converters, photovoltaics, solar power.**

I. INTRODUCTION

In recent years, the subjects of nanotechnology and nanomaterials are the scientific priorities of industrialized countries. The development of nanotechnology and nanomaterials is considered as a new industrial revolution. In the coming decades, the efficiency of nanotechnology will determine the status of every developed nation in the world.

Ukrainian government does not stand apart from these trends. In a joint order of Ministry of Education and Science of Ukraine and National Academy of Sciences of the November 26, 2009 №1066/609 "The approval of the main research directions and the most important issues of fundamental research in 2009-2013 in Ukraine" the sections 1.4.5. "Nanophysics and nanotechnology", and 1.6.5. "Nanostructured (nanodisperse, nanocrystalline) materials" are specially underlined.

The silicon photoelectric converters (PEC) efficiency at level 25-28% and a unit cost 2,0-2,5$/W of generated electric power, impacted on the development of photovoltaic systems. The main directions in this area include photoelectric converters based on monocrystalline, multicrystalline, amorphous silicon, triple-A^3B^5 semiconductor compounds, systems Cu-In-Se [1-5].

II. THE ANALYSIS OF PROBLEMS AND THE FORECAST OF PHOTOVOLTAICS DEVELOPMENT IN UKRAINE.

The overcoming of major obstacles to the development of solar energy - the high cost of electricity and thermal energy, which is generated by solar plants, will be implemented due to a gradual increase in the cost of fossil fuels and the introduction of the environmental component in rates for electricity and heating.

The key factors that have influenced on promoting of the use of solar energy in the world till year 2030:

- the compliance with the Kyoto protocol on greenhouse gas emissions;
- Government support of scientific and technical organizations specializing in the development of highly efficient solar-energy equipment. Creating the necessary legal and economic conditions and mechanisms to stimulate development of solar energy;
- the existence of a scientific and technical human resources, which can ensure development and establish mass production of highly competitive solar energy equipment, as well as construction and operation of solar power plants.

Photoelectric converter production grows 25-30% per year. It is forecasted that their production reaches a value 16 GW in 2012.

The forecast of photovoltaics development is shown in Fig.I.

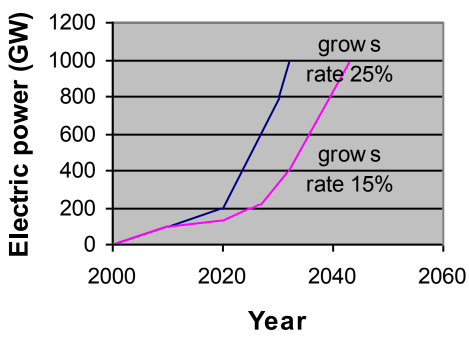

Fig I. The prospect of photovoltaic systems

Table I shows the forecasted volumes and the dynamics of photovoltaics development in Ukraine for the period up to 2030.

Taking into account the current level of technology of converting solar energy into electricity and heating as well as the possible progress in this area over the period up to 2030, we can conclude that a significant contribution to the overall energy balance of the country can be made at the expense of large-scale introduction of two key technologies:

- first phase 2011-2015 – solar photoelectric power plants electricity production distant from the power network. The second phase 2015-2030 – operation in the united energy system of Ukraine.
- the production of low-grade energy by solar installations for partial or full supply of hot water

in the warm season (April-October) for industrial and agricultural enterprises, households, fitness and spa facilities, schools, etc.

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TABLE I. KEY PARAMETERS OF PHOTOVOLTAICS IN UKRAINE FOR THE PERIOD UP TO 2030

Year	Capacity (MW)	Electricity production thousand kWh
2010	60	102000
2015	120	204000
2020	200	340000
2025	300	510000
2030	400	680000

Moreover, we assume the use of solar energy in industrial processes: for the production of fresh water, in water-pumps, in high-temperature metallurgy, in solar refrigeration and domestic refrigeration, in solar dryers and in air-conditioning. Nevertheless, for the period until 2012 the use of solar energy in these technologies will not make a significant contribution to the overall energy balance of the country.

It should be noticed that the development strategy of photovoltaics in the world's leading countries (USA, Japan, Germany, Australia, India, China, etc.) has a goal to cover consumption up to 30%. The concept of global energetic (Fig.II) clearly shows the future grows of solar energy.

Leading Japan companies (Sharp, Kyocera, Mitsubishi) produce photoelectric modules on the basis of multicrystalline, monocrystalline, amorphous silicon, and cover 45% of world production of photoelectric systems (Fig.III) [6].

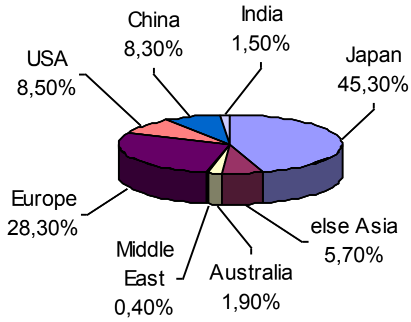

Fig. III. The distribution of world production of photoelectric systems based on multicrystline, monocrystalline silicon. [6]

According to the USA program SAI ("Solar America Initiative") [7], it is provided a strong support for U.S. companies and universities (more than 10 billion $), engaged in the development and large-scale production of photoelectric modules and systems

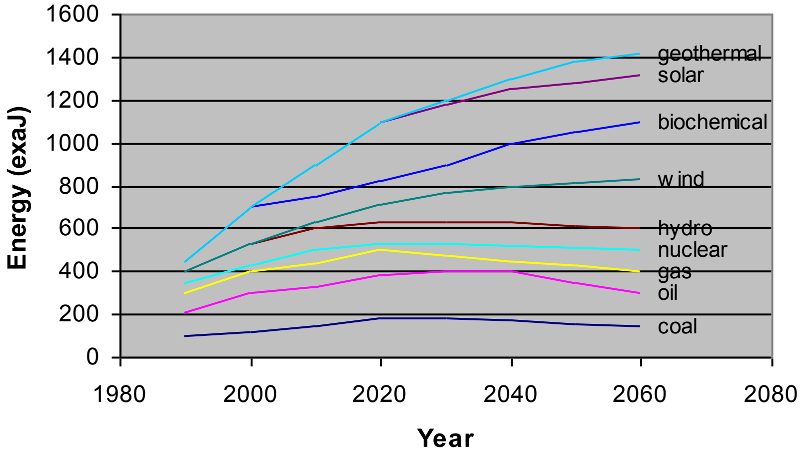

Fig II. The concept of global energetic evolution

TABLE II. FORECAST OF CHANGES IN CONVERSION EFFICIENCY AND THE COST OF PEC.

PEC type	Modern level	Efficiency, % 2010.	Efficiency, % 2020.	Efficiency, % 2030.
PEC based on monocrystalline silicon	13-16 (19)	16 (20)	19 (25)	22 (25)
Thin-film silicon solar cells	10 (14,7)	12 (15)	14 (18)	18 (20)
CIS (Cu-In-Se) – PEC	10–12 (18,9)	13 (19)	18 (25)	22 (25)
PEC based on A^3B^5 compounds	38,9 (40,2)	28 (40)	35 (45)	40 (50)
Electrochemical PEC	(10,5)	6 (10)	10 (15)	15 (18)

. In the scientific aspect it is defined the development of: new low-cost materials with high efficient capacity, chemical stability, efficiency of industrial processes; thin films of semiconductor and organic semiconductors; silicon wafers thinner than 100 mcm; silicon solar cells with conversion efficiency 25%; nanostructured materials; multitransition PES; thermphotoelectric converters; new types of concentrating systems, etc.

To ensure the competitiveness of photoelectric systems (PES) with other sources of energy (fossil fuels, nuclear power, other renewable energy) it is necessary to reduce the cost of a watt peak power of at least 2 times (less than

2,8$/W) and increased to year 2030 the production volume in 1000 times [8-9]. Also, it must be taken into consideration the prevalence of the basic material in the nature, environmental cleanliness, not only finished PES, but their production processes, energy costs of production and a payback period.

Nowadays, more than 90% of the total production of the PES is flat-panel modules made of crystalline and multicrystalline silicon. At this stage of development of photovoltaics in the light of the above, silicon has a leading position. In this direction, it is planned to increase the conversion efficiency from 12-16% to 20-22% due to improved design and technological parameters and to reduce the consumption of silicon by more than 2 times, since 50% of the module is the initial price of silicon wafers. It should be noted that, the use of concentrator and bilateral PEC can be an effective way to reduce the cost [10]. Table II shows the forecast of increasing the conversion efficiency of the basic types of PEC [11].

According to expert estimates in the coming decades it is expected a real "boom" in the industry. It should be noted that the main objectives of this production – improving conversion efficiency and reducing the cost of generated electricity – are impossible without providing cheap raw materials in sufficient quantity and of reducing energy consumption in the manufacture process. Highly efficient photoelectric converters based on gallium arsenide and related materials because of the high cost should be used to power spacecrafts.

The main raw materials for photovoltaic production are polycrystalline, multicrystalline and monocrystalline silicon, which cost has increased recently. Also there are problems with the shortage of raw materials. The cost of the silicon in the price of photoelectric converters (PEC) is at least 50%. It is necessary to develop new technological approaches for reducing the amount of materials used in production combined with flexible adjustment of production to manufacture ultra-thin wafers of “solar” and nanocrystalline silicon. In this case, the risk of production of basic products is dramatically decreasing.

Modern production of photoelectric converters is based on the use of energy-intensive processes, such as thermal diffusion processes, screen printing, in which the operating temperatures reach 1070-1300K. There is a need of creating new heterostructure converters using cheap materials, low-labor and low-energy processes.

The decision of increasing the conversion efficiency of PEC for well-known technologies is usually associated with an increasing of the complexity of production, costs of energy and materials, which leads to an inevitable increase in price. It is usually used the silicon with a high carrier lifetime, which is typical for higher quality, and hence, more expensive silicon. In this aspect it is necessary to develop low-cost technological process that would ensure the improvement of this parameter.

The conversion efficiency of today's photoelectric converters on silicon is relatively low, because of conversion losses of short and infrared solar radiation, losses as a result of surface and bulk recombination, as well as optical reflectivity. It highlights the need for new methods of converting short-wave radiation, technological methods of passivation, gettering and nanostructuring of surfaces.

The solution of these problems will give the opportunity to organize highly profitable production of photoelectric converters and modules; stand-alone energy sources for different purposes; combined photothermogenetarors, that produce both electricity and heating; irrigation systems; drinking water production; photoelectric electrolyzers, portable photoelectric devices for disinfection, etc.

One of the way to reduce the cost of photoelectric modules is to create on their basis the architectural blocks. Energy architectural glass blocks are manufactured for different purposes (for example, ASI Glass, Austria):

- shading to reflect light;
- lighting, light transmission;
- heat;
- solar panels to produce electricity.

TABLE III. PARAMETERS OF THIN-FILM SILICON PEC.

Parameters	Crystalline Si (thin films)	Amorphous silicon	Nanocrystalline silicon	Organic Semiconductors
Unit cost, $/W	2,4-2,7	2,0-2,4	1,7-1,8	1,5
The prospects of reducing the costs, $/W	1,75	1,25	0,9-1	0,5
Conversion efficiency, %	15-20	10–13,6	14-16	5-7

All this can be accomplished with the use of optical coatings and thin-film solar cells. For example, by changing the conditions of film deposition ITO (transparent conductive coatings based on oxides of indium and tin), we can control the opacity of different regions of the spectrum [12]. ITO film can serve as an excellent reflector of infrared (heat) radiation, ie, implement cooling. By changing the conditions of its deposition, we can ensure the transmission of infrared radiation, ie provide heating. The closest prototype unit to produce electrical energy is a solar cell based on amorphous silicon – ASI Thin Film Solar Cells.

III. THE USE OF NANOSTRUCTURED CRYSTALLINE SILICON TO CREATE THIN-FILM PEC

The construction in which a film battery is placed between the glasses remains, but solar battery runs on nanocrystalline silicon with improved technical performance. Foe example, the U.S. company UNI-Solar manufactures thin-film modules on the basis of amorphous silicon (the nearest prototype of the proposed production). In 2006 their solar battery’s capacity was 25 MW. In 2010 - the planned production capacity was 300 MW, ie increased by 12 times.

Table III shows the comparative characteristics of the parameters of thin-film silicon PEC.In nanocrystalline films by changing the size of the nanocrystallites and the band gap can be optimized the layer structure of the PEC for the conversion of various ranges of the spectrum, and thus, theoretically increase the conversion efficiency of 50-60%. These achievements become possible when the technology of thin-film solar cells based on nanocrystalline semiconductors, in particular, nanocrystalline silicon is developed.

Table IV shows the comparative analysis of properties of nanocrystalline silicon and amorphous silicon (on the basis of which, a large-scale production lines are opened in Japan and USA).

Thin-film photovoltaic modules can significantly improve the specific energy characteristics: the conversion efficiency at 8% - 600W/kg, 9% - 1250 W/kg, 10% - 2000 W/kg. That is why they are seen as a close future of photovoltaic systems, including space purposes.

IV. CONCLUSIONS AND CHALLENGING AREAS OF RESEARCH AND DEVELOPMENT

The results of our studies led to creating the photoelectric converters with an efficiency of more than 21% (monocrystalline silicon wafers with size of 100x100 mm).

The main directions of improving the parameters of photoelectric converters are:

- optimization of the parameters of existing converters;
- improving the manufacturing technology of PEC in order to reduce material and energy costs of its production;
- the appliance of new materials in PEC technology.

From the authors point o view, the following ways to improve the efficiency of PEC are possible:

1. Development of technological methods of producing photoelectric structures that preserve the quality of the original semiconductor. The solution of this problem gives a rise of carrier lifetime, which accordingly increases the rate of collection of photogenerated charge carriers.
2. Creating a specially located doped regions in the semiconductor material that create the so-called pulling electric field in three-dimensional space, which increases the mobility of charge carriers in the direction of current collectors.
3. The extension of the PEC absorption spectrum in the direction of the ultraviolet and infrared spectral regions.
4. Decrease the series resistance of the contact transition zones and contacts.
5. The use of new, more efficient optical and protective coatings.
6. Creation of new types of heterojunctions using alloys of amorphous and nanocrystalline silicon.

TABLE IV. COMPARATIVE CHARACTERISTICS OF THE PROPERTIES OF AMORPHOUS AND NANOCRYSTALLINE SILICON [12-16]

Parameters	Amorphous silicon	Nanocrystalline silicon	Nanocrystalline silicon (Section III of this paper)
1. Band gap, eV	1,75	1,96–2,2	1,85–2,25 (depending on the size of crystallites and the properties of the interface)
2. Electron mobility, $cm^2/V \cdot s$	0,1	40	42-45
3. Hole mobility, $cm^2/V \cdot s$	0,001	0,2	0,22-0,25
4. Photosensitivity (the ratio of photoconductivity to dark conductivity)	7· 103	5· 105	(5,6–6,4)· 105
5. Photosensitivity heterostructures in the visible range, mA/lm	12	45	79-135
6. Photosensitivity of the heterostructures at a wavelength of 350 nm, A/W	0,3-0,35	0,4-1,1	6,95
7. Degradation level, %	30-35	10-15	8-10
8. Manifestation of the degradation effect Staebler–Wronski	yes	no	no
9. Toxicity of the process	yes	yes	no

REFERENCES

[1] *Наноэлектроника: монография в двух книгах. Кн. 1. Введение в наноэлектронные технологии* / Г. М. Младенов, В. М. Спивак, Е. Г. Колева, А. В. Богдан.– Киев-София: Аверс, 2010. – 334 с.

[2] *Наноэлектроника: монография в 2 кн. Кн. 2. Наноструктурированные материалы и функциональные устройства* /Ю.И. Якименко, А. Н. Шмырева, Г. М. Младенов, В. М. Спивак, Е. Г. Колева, А. В. Богдан; под общей редакцией действительного члена Национальной академии наук Украины Ю.И. Якименко. – Киев-София: Аверс, 2011. – 394 с

[3] Green M.A. *Third generation photovoltaic – theoretical and experimental progress* // Proc. of the 19 th European Photovoltaic Solar Energy Conf. and Exhibition. – 2004. - Paris (France). - P. 12 - 19.

[4] Roca F., Carabe J. *Silicon heterojunction cells* // Proc. of the 19 th European Photovoltaic Solar Energy Conf. and Exhibition. - Paris (France). - 2004. - P. 1321 - 1328.

[5] Longo C., De Paoli M. Dye – *Sensitized Solar Cells: A Successful Combination of Materials* // J.

Braz. Chem. Soc. - 2003. - Vol. 14, № 6. - P. 889 – 901.

[6] Aratani F., Goto S. *The Present status and future direction of technology development for photovoltaic power generation in Japan* // Proc. of the 20 th European Photovoltaic Solar Energy Conf. - Barcelona (Spain). - 2005. - P. 2846 - 2849.

[7] Barnett A., Honsberg C., Kirkpatrick D. *New US Ultra High Efficiency R&D Programme* // Proc. of the 21 th European Photovoltaic Solar Energy Conf. - Dresden (Germany). - 2006. - P. 124 - 128.

[8] Swanson R.M. *A Vision for crystalline silicon solar cells* // Proc. 19 th European Photovoltaic Solar Energy Conf. - Paris (France). - 2004. - P. 968 - 974.

[9] Унтила Г.Г., Кост Т.Н., Чеботарева А.Б., Закс М.Б., Ситников А.М., Солодуха О.И. *Новый тип высокоэффективных двусторонних кремниевых солнечных элементов с внешними шинами и проволочной контатной сеткой* // Физика и техника полупроводников. - 2005. - Т.39, Вып.11. - С. 1393 - 1398.

[10] Gasman L. *Thin film and organic PV: New Applications for solar energy* // Nanomarkets. - 2006. - P. 1- 61.

[11] Arya R.R. *Technology and market challenges to mainstream thin – film photovoltaic modules and applications* // Proc. of the 19 th European Photovoltaic Solar Energy Conf. - Paris (France). - 2004. - P. 2024 – 2029.

[12] Repmann T., Appenzeller W. *Advanced PECVD processes for thin film silicon solar cells on glass* // Proc. of the 19 th European Photovoltaic Solar Energy Conf. - Paris (France). - 2004. - P. 1334 - 1339.

[13] Jun K.N., Stiebig H. *Amorphous silicon multilayer solar cell deposited by PECVD method* // Proc. of the 14 th European Photovoltaic Solar Energy Conf. - Paris (France). - 2004. - P. 1387 - 1390.

[14] Hofmann M., Glunz S., Preu R., Willeke G. *21% - efficient silicon solar cells using amorphous silicon rear side passivation* // Proc. of the 21 th European Photovoltaic Solar Energy Conf. - Dresden (Germany). - 2006. - P. 124 - 128.