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Technology of photovoltaic modules: physical principles of functioning of solar cells

One of the foci of the forth-coming world exhibition the EXPO to be held in Astana, Kazakhstan in 2017 is devoted to the sustainable alternative energy. On the one hand, photovoltaic is one of the areas of energy industry, which belongs to a sector of the renewable sources. On the other hand, it is a realm of technology of the photoelectric devices, which are based on the physics of semiconductors. In this article the convertors of the solar radiation into electricity – so-called solar cells - are discussed. The important key of functioning of the solar cells is a photoeffect, a physical phenomenon of the direct transformation of the sunlight into electric current. The semiconductor p-n junction governs the process of the appearance of the photovoltage. The operation principles and manufacturing structures of various solar cells and their applications are considered. The topic is provided on the introductory level without going deeply into details of the photovoltaic research and condensed matter physics. Many aspects of solar batteries are explained rather qualitatively, that would be interesting also for students and scientists of non-physics education.

Key words: solar energy conversion, photovoltaic engineering, solar cells, ecology, environment protection, photoelectric modules, solar radiation generator, renewable sources of energy, photo effect.

И.Х. Жәрекешев

Фотовольтаикалық модулдердің технологиясы: күн сәулесі элементтерінің физикалық принциптері

Қазақстан Республикасы астанасы – Астана қаласында өткізілетін EXPO-2017 дүниежүзілік көрменің негізгі тақырыптарының бірі – балама энергетика. Фотовольтаика – бірінші жағынан, энергияның қайта қалпына келтірілетін көздерінің басты секторына қатысты келешектің индустриясы іспетті құбылыс. Екінші жағынан, ол жартылай өткізгіштік құралдар физикасының негізінен саналатын фотоэлектрлік түрлендіргіштердің барлық технологиясын қамтиды. Мақалада күн сәулесі радиациясын электрлікке түрлендіретін – күн сәулесі элементтері қарастырылған. Кез келген күн сәулесі элементінің жұмыс істеуінің негізгі принципі – жарық сәулелерін электр тоғына тікелей түрлендіретін физикалық құбылыс – фотоэффект болып табылады. Әртүрлі күн сәулесі элементтерін жасап шығару әдістері мен қызмет атқару принциптері және оларды пайдалану мәселелері талқыланған. Энергия нарығында күн сәулесін түрлендірудің экономикалық мүмкіндігі және бәсекеге қабілеттілігі қарастырылған.

Түйін сөздер: фотоэлектрлік, күн энергиясын түрлендіру, күн көзі элементтері, экология, фото-жаңғырткыштар, фотоэффект, жартылай өткізгіштік технологиясы, қайта жаңартылатын энергия көздері, альтернативтік энергетика.

И.Х. Жарекешев

Технология фотовольтаических модулей: физические принципы работы солнечных элементов

В предстоящей всемирной выставке EXPO-2017, которая будет проводиться в столице Казахстана, г. Астана, одной из основных тем является альтернативная энергетика. Фотовольтаика, с одной стороны, представляет собой сектор возобновляемых источников энергии – важную область индустрии будущего. С другой стороны, она охватывает всю технологию фотоэлектрических преобразователей, основой которых является физика полупроводниковых приборов. В этой статье рассматриваются солнечные элементы – преобразователи солнечной радиации в электричество. Ключевой принцип работы любого солнечного элемента заключается в фотоэффекте – физическом явлении прямого преобразования световых лучей в электрический ток. Полупроводниковый p-n переход управляет процессом возникновения разности

потенциалов. Обсуждаются принцип действия и способы изготовления различных солнечных элементов и их применение. Тема представлена на качественном уровне без подробного изложения физики полупроводников и фотоэлектрических приборов. Многие аспекты солнечных батарей могут быть интересны для студентов и специалистов нефизического образования и смежных с физикой специальностей.
Ключевые слова: фотоэлектричество, преобразование солнечной энергии, фотоэффект, солнечные элементы, экология, солнечные модули, фотопреобразователи, возобновляемые источники, альтернативная энергетика

1. Introduction

The Sun is one of the giant and maybe the most effective energy source, which is available for the mankind. Even from such a huge distance of 150 million kilometers it delivers a colossal amount of energy to the Earth's surface in the form of the radiation. The every-day portion of energy coming from the Sun to us exceeds in 15,000 times daily consumption of the whole population of our planet. The total irradiative capacity of the star is equal to $3x10^{23}$ kW approximately, the total power being about $1,75x10^{14}$ kW, which directed only for illumination of the surface of the Earth. Suppose theoretically, that only three percents of the Sahara desert are covered by the solar plants. Then the energy converted from the sun radiation is more than enough to satisfy fully all the energy demand of Europe and Africa together [1].

There are two ways of the conversion of the sun radiation into energy for human use [2]. The one of them is the solar thermal technology, i.e. a technical process of transforming the solar radiation into thermal energy, for instance, into heating, warming etc. The other one is photovoltaic method, implying the conversion of the visible sun light into electric energy, that is, into the electric current. The later is actually a topic of my article.

The term 'photovoltaic' consists of two words, the first part comes from the ancient Greek 'photos' meaning 'the light', while the second part stems from the name of the Italian physicist Alexandro Volta, in the honor of whom the Volt (V) - the unit of measuring of the potential difference - has been called. Correspondingly, the voltage is referred to as the difference of the electric potentials. Thus, the photovoltaic process is an appearance of the voltage between the opposite contacts of a solar cell under the direct light irradiation. The physical principle is based on the phenomenon known as a photoelectric effect (shortly, photoeffect) discovered experimentally in 1839 by the French scientist A.-E. Bekkerel. Much later on, the famous physicist Albert Einstein has explained this effect theoretically and won the Nobel Prize in 1905.

Basically, the term 'photoeffect' is understood as a process of taking out (emitting) of free charge carriers from a solid by means of radiation. Two types of the photoeffect are distinguished: internal and external ones. The first photoelectrical cells called also as the solar cells (SC) have been elaborated in 1950. Starting from this time, however, the SC are used everywhere in our life, from pocket calculators to cosmic stations and satellites. In the literature one encounters with the widely-spread abbreviation «PV», which stays for the word 'photovoltaic'.

2. Types of the solar cells

The solar cells are usually made from crystalline silicon of high purity. Despite, that the chemical element Si occupies 27 percent of our planet shell, it is seldom to find it in the nature as pure crystals, rather in the compounds of quartzite or in conventional sand (SiO_2) with various impurities. For the artificial growing very pure monocrystals, with the level up to 99,9999999%, an expensive fabrication equipment is needed. Thus, the raw input material to be cut into thin films and wafers becomes too costly. This type of silicon is called semiconducting Si.

The solar modules can be constructed from mono-crystalline or polycrystalline silicon, as well as created by the use of the thin-film technology [1]. The market segment of the crystal-type SC comprises 80% of the entire silicon photovoltaic. This is because they possess relatively long ‚life-time'. However, the demands in a large amount of initial raw materials and long time of the process of the crystal growth belong to their disadvantages. Taking the costs into account, other growth technique compare favorably with the above one. It goes towards diminishing the thickness of the silicon layer of SC, and, as a rule, produces the square form of SC with the conventional sizes of 0.125 м by 0.125 м.

There are also even smaller samples, e.g. with the sizes of $10x10см^2$, which are more expensive in handling. This is due to the fact that for generating the same amount of power, one needs more solar cells. Recently the 6-inch SCs have appeared. The latter are more convenient for further developing and markedly cheaper than the former ones. However the old current invertors encounter certain problems because of the increased over 35% value of the electric current.

The monocrystalline solar cells consist of the planar films which are cut from the bulk pure crystal of silicon, grown from the melted quartz sand. The thickness of the substrates is equal to about 0,3 мм. Since the crystals of highest purity almost without imperfections are used, the costs of the monocrystalline solar cells are relatively high due to expensive technology and accompanied facilities. Therefore they are exploited mostly for in the autonomic set-up for energy supply of satellites and cosmic stations. During last decades the efficiency of the monocrystalline SC used in the industry of the alternative energy sources has increased upto 16%, while in the laboratory conditions the peak values of 19% are reached. It is well known that maximal efficiency of the conversion lies in the range of 27-29%, which is the upper limit according to the theory semiconductor devices.

The polycrystalline solar cells have smaller efficiency, about 13-15%, compared to the monocrystalline counterparts. They comprise many layers of silicon, which have been cut off from a pressed block, which consists of several perfect Si-crystals, the symmetric axes of which are orientated with various angles to each other. One can recognize the polycrystalline SC upon well seen boundaries between various domains with different colors, while the monocrystalline solar cells are homogeneous and of the same color. Поликристаллические СЭ узнаются по хорошо различимым границам зерен, в том время как монокристаллические СЭ выглядят одноцветно и равномерно. It is clear, that the price of the polycrystalline SC should be lower than of the monocrystalline type due to smaller efficiency.

The thin film solar modules are fabricated, as a rule, from the layers of the semiconducting compounds, which are deposited on the glass or metallic substrate. The thickness of the layer is approximately 100 times less than their crystalline analogs. For the former ones it ranges from 1 μm to 5 μm, while for the latter it is of 200-300 μm. Currently, various chemical compounds are used to fabricate thin-film SC, for instance, amorphous silicon, denoted as a-Si, CIS - cupper-indium-diselenide, alloys of CdTe, CdHgTe, CdPbTe etc. The efficiency of energy conversion of the above compounds was rather low, at the very beginning from 5 to 10 percent. Nowadays it can exceed 13 percent. They have found applications in pocket calculators and hand watches.

The technology of amorphous silicon is simpler, i.e. one does not need long-time for growing up the crystals and the expensive cutting facilities. However, the processes of degradation, related to the Stabler-Wronsky effect, result in the lost of functionality, and therefore the efficiency of the solar cells made from a-Si undesirably decreases. Particularly in the first few months the efficiency can drop significantly. Often the photoelectric cells are made from amorphous silicon modified by hydrogen (a-Si:H). The atoms of hydrogen are introduced into a-Si with the goal to passivate the dangling bonds. Also for the solar cells from the compounds CdTe a quick and inexpensive serial production is possible. One of the drawbacks is that Cd and Te are highly toxic materials. The constraint for the wide production of CIS-modules is insufficient exploration of indium all over the world. According to statistical agencies, the portion of the thin-film solar cells in the photovoltaic market amounts 18,5% and can reach the level of about 29% in 2016.

A combination of the crystalline and amorphous SC leads to a so-called HIT-cell – a heterostructure with a thin inner layer. The efficiency of the HIT can go upto 17%. The structure of the HIT cell looks as a multilayered sandwich, the substrate from monocrystalline silicon is deposited by thin layers of amorphous silicon from the both sides.

3. Functioning of the solar cells

The principle of the operation of semiconducting photovoltaic convertors defines a foundation of the whole semiconductor technology. The initial material, e.g. silicon, is doped with various impurity atoms, i.e. one makes the material dirty intentionally, however the introduced imperfections being under control. Due to that the silicon with impurities becomes more conductive. If the sunlight shines onto the surface of the solar cell, then the electrons of silicon atoms are given with the energy of the photons. This energy is enough to push out the electron from the atomic orbit (the process of the atom ionizing). However it can happen, provided that the energy of the photon is larger than a certain threshold magnitude. The electrons being free can travel through the crystal lattice almost without resistance. The negatively charged electrons are activated from the valence band to the conduction band, jumping over the energy gap. In the valence band remain the positively charged holes. Both types of the charged carriers are displaced in opposite directions away from the active region of the p-n junction, as shown in the Fig. 1.

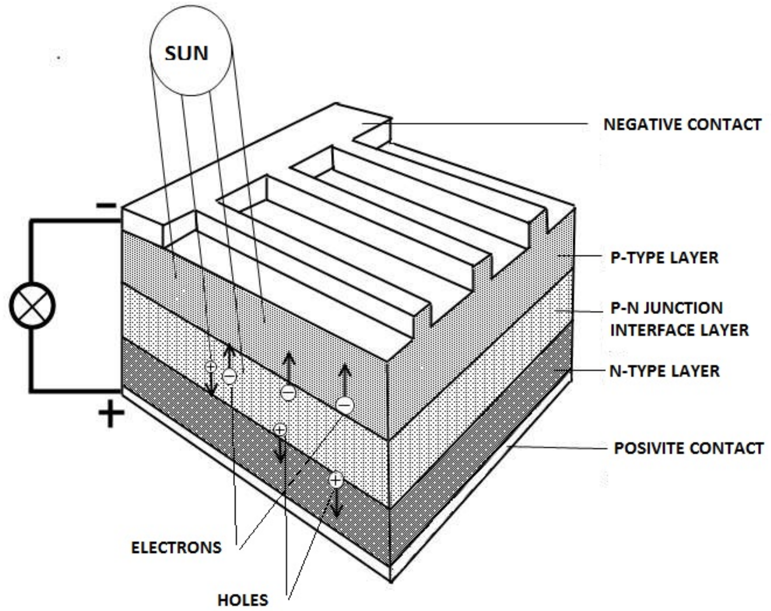

Figure 1 – Cut-off scheme of the silicon solar cell.

In the physics of semiconductors this process of creation of electron-hole pairs under the light irradiation is called the inner photoelectrical effect. The minimal energy to create these pairs is referred to as ‚output work’. The detailed description of the photoeffect in semiconductors and its theory can be found elsewhere in the literature and goes beyond of the scope of this paper. We restrict ourselves only by a qualitative introduction to the physics of the solar cells, which is quite enough for understanding the photovoltaic as a component of the alternative energy sources In order to that the electron-hole pairs do not annihilate (the process of recombination), the intrinsic electric field is built-in artificially, which removes electrons and holes from the their creation place away in different directions. Imposing the built-in electric field does not require an additional energy effort. The semiconductor technology allows one to manufacture a layered structure, often called a p-n-junction. The upper layer of the silicon substrate is doped by the atoms of P, while the lower layer is doped by the atoms of B. With respect to the silicon with four valence electrons, the P atom with five valence electrons is negatively charged, while the B atom with three electrons is positively charged. As a result, at the interface of the p-n-junction the two spaced charged areas are generated, which are the reason of the intrinsic electric field (see Fig. 1.).

If the upper and the lower parts of the solar cell are electrically connected via a circuit, then the non-equilibrium excess electrons, generated due to illumination, move towards the positive pole, while holes move towards the negative pole. This flow of the charge carriers is the photoelectric current, and comprises a key point of the whole photoelectricity. Thus, a consumer connected to the external circuit receives electric energy. If the circuit is disconnected, then the photoelectric voltage appears at the external contacts of the solar cell. The orientation of the poles of the photovoltage is opposite to those of the intrinsic electric field. In order for electrons to collect all over the surface of the SC, thin metallic contacts are deposited on its top. One can easily see these metallic strips on the solar batteries.

The magnitude of the photovoltage depends on the type of the semiconducting material. For silicon this is about 0,5 - 0,6 V. One can estimate electric power of the Si solar cell of the size 10см x 10см with the efficiency of 16%. At the constant current of 2.6 A, the power is equal to 1.6 W. However such a low voltage is often useless, therefore a series of the solar cells are connected subsequently, so that the total sum voltage increases. An ensemble of the SC is aligned in a string. The parallel connection of several strings allows one to increase in addition the value of the electric current. The final combination of the consequent-parallel ordering of the linked SC is integrated into a unit solar module.

The voltage on the contacts of the SC depends weakly on the intensity of the sun radiation, while the electric current drastically grows with larger illumination. The silicon cell with the active area of 100 cm^2 provides the maximal electric current of about 3 A at the incident sunlight with the power density of 1000 W/m^2.

It should be taken into account that the efficiency of the solar cell is substantially affected by the temperature. A strong heating of the solar cell leads to significant lowering of the power of the SC. As a consequence, the efficiency of the conversion decreases, that is undesirable. For instance, for each degree in increasing the temperature, the efficiency of the Si cell drops in value on a half of a percent, and the efficiency of the SC made of amorphous Si does approximately on a quarter of a percent.

The general power of the photovoltaic module is measured in kilowatts of the peak power, denoted by kW_p and is determined by the norms of the testing conditions. The standard test conditions (STC) consist of several parameters, namely, the light radiation density of 1000 W/m^2, the module temperature of 25^0C, and the coefficient of the air mass (AM) of 1,5. The latter defines which volume of the atmospheric air the sunlight goes through, unless it falls down on the solar module surface. The AM coefficient on the equatorial region equals one, because the sun rays drop almost perpendicular to the Earth's surface, travelling along the shortest way. Under oblique position of the Sun the sunlight travels the longer path through the atmosphere. The ratio of this longer light trajectory and the shortest path at the equator provides the value of the Air Mass. It is imperative to account for the AM magnitude, since the spectral distribution of the sunlight changes, while going though the atmosphere of our planet. The reason is that some parts of the sun spectrum are absorbed by the air more intensively, therefore the spectral characteristics for shorter wave lengths are more pronounced.

4. Concentrated photoelectric convertors

The solar modules can differ from each other on the operation principles, construction designs and goals of appliance. Except of the conventional planar geometry there are photoelectric convertors with the parabolic form of the reflector, which are widely spread in application. The parabolic reflecting mirror concentrates the sunlight onto a small area, where the solar cells are placed. In spite of the advantage that the efficiency of the concentrated conversion drastically grows compared to usual stationary firmly-mounted systems, it is necessary to change all the time the angle of the mirror reflector, in order to track the trajectory of the Sun. Focusing on the sun direction requires additional efforts that costs energy. Another solution is a concentrator photoconvertor working on the Fresnel lenses [3]. As distinct from the parabolic solar modules, which focus the radiation after reflecting it from the mirror, the transparent Fresnel lenses concentrate the sunlight after going through them, i.e. after refracting. The sun concentration degree can be very large; it exceeds over hundred times the limit of the parabolic geometry of the solar module.

Since the strongly concentrated sunlight leads to the significant increase of the temperature, an additional opportunity appears to exploit an excess of the heat in order to warm the water [4]. Thus, the concentrator photovoltaic module gains the properties of a thermal collector. Note, this combination gives an extra advantage. The solar collector can produce the electricity and the heat simultaneously [4]. The united system of the photovoltaic convertor and the solar collector, optimally developed (from the viewpoint of the energy save) in one operating unit is called hybrid-CPVT system. It allows one to perform both types of conversion of the sun energy in the frames of the only single device. This means physically, that various domains of the sun spectrum - infrared and visible – are transformed into useful forms of energy along two different technological channels, integrated however in the one thermal & photovoltaic concentrator module [5].

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