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INNOVATIVE THIN-FILM HELIOTECHNOLOGIES OF DECARBONIZATION AND ECOLOGIZATION OF MUNICIPAL ENERGY OF UKRAINE

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Abstract. Today, among renewable energy sources, solar power is particularly effective. It is known that solar panels are mainly (more than 95 %) based on monocrystalline or polycrystalline (sometimes amorphous) silicon, as a unique semiconductor material. Its irreplaceability is explained by its prevalence in nature, at the same time, the technology of manufacturing silicon solar cells is quite complex and energy-intensive. Therefore, scientists of the world today are working on the search for new materials, in particular, binary, ternary, non-stoichiometric and other compounds They also have satisfactory electrophysical characteristics, however, at present, these tandem and more complex materials have, compared to silicon, significantly lower efficiencies and problems with the timing of their operation. In addition, the absolute majority of them are rare in nature and therefore industrial production is quite problematic.

Keywords: solar energy, solar panels, thin-film solar cells, decarbonization, renewable energy gels.

1. Introduction

The sun, like some other natural sources (wind, geothermal, biogas, etc.) is a giant renewable and inexhaustible source of energy for humanity and, in particular, for its utility energy and infrastructure. The growth trend of solar generation, like other RES, is irreversible (Savchuk, 2019). At the same time, humanity has the Sun in its arsenal, as an endless source of energy, and natural materials for the implementation of solar-generating technologies (Sembery, Tóth, 2004). We are talking, first of all, about silicon (silicon), as a unique semiconductor material, about 30 % of which compounds in the earth's crust (quartz, sand, silica, salts of silicic acid and many other silicon-containing compounds) (Horath, Szabo, 2018). Due to the prevalence of this unique semiconductor material in the earth's crust, it is currently the best material for the production of solar panels (Ivanov, 2021). At the same time, world scientists are searching for other affordable and energy-efficient solar technologies, in particular thin-layer and thin-film composite semiconductor compounds, which are quite promising. So, at this stage, there are the following manufacturing technologies for solar batteries: 1-silicon (1st generation); 2-thin film (2nd generation); 3-synthesis on organic compounds, including carbon-containing compounds (3 generations). At the same time, silicon technologies currently make up more than 95 % of the solar energy generation market. (Petruk et al., 2024, Richart, 2015).

2. Materials and Methods

Analysis of short characteristics of tandem and more complex semiconductor compounds

Compounds of type $A^{III}B^{V}$. These are compounds of chemical elements of III and V groups of the

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periodic system of chemical elements. The crystal structure of their sphalerite type. The chemical bond is mostly covalent, but up to 15 % has an ionic component. The most important representatives of this group (Mirkin, 2024): GaAs, InP, InAs, InSb – direct bandgap semiconductors, with the exception of GaP. Representatives of this group of binary compounds can also form non-stoichiometric solid solutions of double, triple and more complex structures, for example: GaAsxP1-x, etc. (Sembery, Tóth, 2004).

Tandem and complex semiconductor compounds for solar energy generation

Type of compound	Crystalline structure	Chemical bonds	The width of the forbidden zone	The most important representatives
$A^{III}B^{V}$	Sphalerite	Mostly covalent	~1 eV, GaAs→1.4eV	GaAs, InP, InAs, InSb
$A^{II}B^{VI}$	Cubic or hexagonal	Ionic-covalent	~1 eV, CdTe→1.5eV	CdTe, CdS, ZnTe, ZnSe, ZnO, ZnS
$A^{IV}B^{VI}$	Orthorhombic	Mostly ionic	~1 eV, PbS→0.35eV	PbS, PbSe, SeTe
$A_2^{III}B_3^{VI}$	Sphalerite	Ionic-covalent	2–3 eV, Ga_2Se_3→1.2–2 eV	Ga_2Se_3, Ga_2Te_3, In_2Te_3
$A^{II}B^{IV}C_2^{V}$	Chalcopyrite	Ionic-covalent	1-2 eV	$CdSnAs_2$, $CdGeAs_2$

Compounds of type $A^{II}B^{VI}$. They can have the crystal structure of both sphalerite and wurtzite. The connection is ionic-covalent (45–60 % of the ionic component). Some representatives can be implemented in the form of cubic and hexagonal structures. The most important compounds of this group are: CdTe, CdS, ZnTe, ZnSe, ZnO, ZnS, etc. They can also form a continuous series of solid solutions, including those with a non-stoichiometric structure and corresponding point defects, which can have significant electrical conductivity (electrical activity), which is important for the process of converting solar energy into electrical energy.

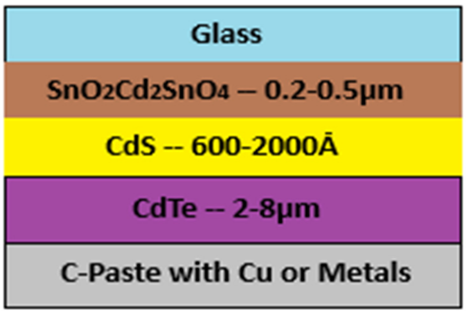

Fig. 1. An example of a fragment of a composite thin-film solar cell based on binary (tandem) and more complex semiconductor compounds

Compounds of type $A^{IV}B^{VI}$. These are compounds with a crystal lattice of the NaCl type with an orthorhombic structure and also with an ionic-covalent (mostly ionic) bond type. Here are examples of these compounds: PbS, PbSe, PbTe, SeTe, etc.

Compounds of type $A_2^{III}B_3^{VI}$. They have a sphalerite structure with typical representatives: Ga_2Se_3, Ga_2Te_3, In_2Te_3, etc.

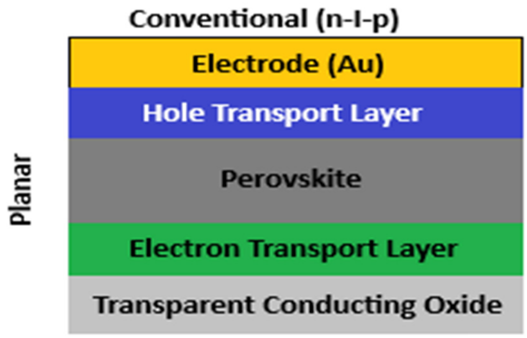

Fig. 2. An example of a thin-film (thin-layer) solar cell based on perovskite

Triple compounds of type $A^{II}B^{IV}C_2^{V}$. Chalcopyrite lattice. Typical representatives: $CdSnAs_2$, $CdGeAs_2$, etc.

$A^{IV}B^{IV}$ compound represents silicon carbide SiC. At the same time, beta-SiC (sphalerite), and alpha-SiC (hexagonal structure). Refractory semiconductor, so its use in solar generation is problematic due to high synthesis temperatures, hardness, and complex technology of solar cell formation, etc.

3. Results and Discussion

All of the semiconductor compounds listed above have a band gap of around 0–3 eV. They are made either by direct or indirect methods of synthesis, that is, with the help of chemical reactions, or by hot pressing of powders, or fusion, for example, in quartz ampoules. At the same time, if the synthesis is below the melting point, then a compound of non-stoichiometric composition with corresponding structural defects in the form of small crystals or an epitaxial film is obtained (Green, 2019). For some semiconductor binary or more complex compounds, the method of zone melting is used, for example: for indium antimonide, or the method of extracting a single crystal from the melt (Czochralski method) – for mixtures containing silicon or germanium. As a result, a single crystal with a certain planar orientation and with appropriate acceptor or donor impurities with charge carrier concentrations in the range of 10^{18}–10^{19} cm^{-3} is obtainned·(Chekunova, 2021). Let us recall that the conversion of solar energy into electrical energy occurs at the boundary of the created np-junction in the near-surface region of a semiconductor plate, layer or film. It is the excess electrons excited by light quanta that recombine in this region with holes in the valence band, overcome the forbidden band and pass into the conduction band. Further, under the influence of an external applied voltage or potential difference, they cause the emergence of a direct electric current, which, if necessary, can be converted into an alternating current with the help of an inverter.

For tandem compounds and perovskite film technologies, there is a problem of the complexity of their manufacture, pricing, and the strength and life of the cells (Machín, Márquez, 2024). Therefore, their development at the current stage is at the stage of R&D, pilot projects, or even partial market entry. At the same time, thin-film semiconductor materials have a thickness of several microns. They are formed mainly from amorphous silicon, or silicon-free technologies are perovskites ($CaTiO_3$), or based on cadmium telluride (CdTe), or copper-indium-gallium diselenide, etc. At the same time, films based on the relatively affordable mineral perovskite are relatively easy to manufacture, but at the same time have a low efficiency (initially 3–4 %, but today in some cases the efficiency of their conversion of solar energy is even up to 24 %). However, perovskite technology still faces some obstacles: low strength and durability, moisture resistance, the need for encapsulation through a layer of glass or aluminum oxide, which significantly reduces their efficiency.

Technologies for the production of photocells from gallium arsenide, indium antimonide, cadmium telluride and other most commonly used semiconductor binary compounds, although they have a fairly high efficiency of around 20–23 %, and gallium arsenide sometimes even up to 35 %, but their rarity restrains the market, and therefore impossibility of production on an industrial scale. At the same time, the latest photovoltaic technologies include several types of hybrid tandem cells with an efficiency of up to 46 %. However, the market is held back by their cost and the complexity and subtlety of technological processes of synthesis. Interesting are heterostructural elements with the simultaneous use of monocrystalline silicon, as well as Topcon technology with passivated contact cells with an efficiency of up to 28 %. Tandem solar cells are several layers with selective bands for converting radiation into electricity. Double-sided solar cells with an efficiency of 27 % or more are also known, and double-sided ones based on AsGa are up to 70–75 %. But at the same time, both arsenic and gallium are quite scattered chemical elements, so their extraction on an industrial scale is quite problematic.

The latest photovoltaic elements known today (Komoto, Jin-Seok, 2018; Jaeger-Waldau, 2020), made from a promising group of photovoltaic materials – transition metal dichalcogenides (TMD), developed by scientists at Stanford University, can become the basis of ultra-light solar panels. Such new film solar cells could eventually be used for mobile applications, from handheld devices and autonomous transmitters to drones, light aircraft and electric cars. The main advantage of TMDs is that, compared to other solar materials, they are able to efficiently absorb ultra-high levels of light, and they also use radiation from a part of the spectrum that is not available to other types. A TMD element is able to overcome a typical problem for this type of photovoltaic devices – the so-called Fermi level. The scientists used graphene contacts to mitigate the effects of this phenomenon and achieved a record power-to-weight ratio of 4 W/h, which is currently on par with current commercial thin-film PV cells. Previously studied TMDs could not convert more than 2 % of sunlight into electricity, while for silicon this figure is closer to 30 %. The Stanford prototype has already achieved an efficiency of 5.1 %. Moreover, it showed 100 times higher specific power than any other thin-film photovoltaic cell created to date. The authors of the invention are confident that through optical and electrical optimization they can achieve an efficiency of 27 %.

However, the greatest achievement of scientists is the thickness of the photocell, which is only a few hundred nanometers. The prototype consists of molybdenum oxide, tungsten selenide and gold contacts located on a layer of graphene one atom thick. All this is between the flexible polymer and the anti-reflective polymer shell, which increases light absorption. In general, the thickness of such TMD elements is less than 6 μm.

At the same time, it is better to choose other types of panels for the northern regions of the globe, but the closer to the equator, the better are monocrystalline panels. Due to the structure of amorphous silicon, silicon batteries effectively absorb photons of scattered light. Silicon solar panels are ideal for northern areas where vast areas are empty. At high temperature, the performance of silicon panels is less than that of analogues, but is still sufficient for domestic consumption. A thin-film solar panel works effectively with diffuse radiation, is cost-effective in regions with foggy and cloudy climates or in industrial areas with difficult environmental conditions (smoky and dusty). Thin-film panels are inexpensive, but due to their lower efficiency, they also require more space than their predecessors.

From an ecological point of view, it will be necessary to prevent the processes of degradation of panels and, especially, to manage in the distant perspective the volumes of decommissioning of CE solar panels (cells), their processing and reuse, or disposal.

At the same time, the following can be attributed to the factors that influence the development of CE in Ukraine:

– joining Ukraine to the European “Green Course”;

– preservation of state support for RES producers until 2030;

– improvement of the wholesale electricity market;

– high cost of electricity from RES;

– the vulnerability of the final consumer due to the increase in tariffs;

– non-fulfillment by state energy companies of their obligations to fully pay debts to RES sector producers;

– Ukrainian society’s request regarding “clean” sources of energy, etc.; At the same time, today the latest technologies of thin-film-thin-layer solar cells are confidently advancing on the way to wide industrial production (Chekunova, 2021).

4. Conclusions

Therefore, silicon technologies for the production of solar panels have no alternative today, since silicon (sand and silica) in the earth's crust is about 30 %. However, the technologies for obtaining solar cells from monocrystalline (and polycrystalline, and amorphous) Si are quite expensive and complicated, since they are carried out in the vicinity of 1.5 and more thousand oC. Therefore, scientists of the planet continue intensive searches for more accessible thin-film (thin-layer) solar technologies. However, at this stage of the development of solar energy generation, they also have serious drawbacks, namely: dispersion and low concentrations of natural materials for binary and more complex semiconductor compounds, which makes their production on an industrial scale impossible. There is hope that in the near future, thanks to allotropic modifications of carbon, namely: graphene, carbine, fullerene, nanotubes and nanorings, mankind will be able to solve the problems of significantly increasing the efficiency of solar generation of environmentally clean energy. New discoveries are also possible in non-stoichiometric ceramics, tandem cells of the hybrid type, heterostructural elements with the simultaneous use of monocrystalline silicon, double-sided solar cells based on GaAs, as in space stations, as well as perovskite thin film technologies, etc. In any case, the main task of the scientists of the world is not only to simplify the energy consumption of modern solar technologies, but, first of all, to significantly increase the efficiency of solar panels, and in general, RES.

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