THIN FILM PHOTOVOLTAIC TECHNOLOGIES: STATUS AND PERSPECTIVES

TANKOSLOJNE FOTONAPONSKE TEHNOLOGIJE: TRENUTNO STANJE I IZGLEDI

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Today, the renewable energy systems have a significant impact on the environment. One of the most promising renewable energy technologies is photovoltaic (PV) energy conversion, which represents the direct conversion of sunlight into electricity. Commercial PV materials commonly used for PV systems include solar cells of silicium (Si), cadmium-telluride (CdTe), coper-indium-diselenide (CIS) and solar cells made of other thin layer materials. In this paper we will focus on the different thin film photovoltaic technologies, actual market situation and future challenges arising with growing PV demand. Also we will point out the advantages of the thin film photovoltaic technology for building integration, because the Building integrated Photovoltaic (BIPV) market is still one of the big hopes for thin film technologies.

Keywords: *Thin film Photovoltaics, technology, building integration.*

U današnje vreme sistemi koji koriste obnovljivu energiju imaju značajan uticaj na životnu sredinu. Jedna od najperpsektivnijih tehnologija koje koriste obnovljivu energiju jeste pretvaranje fotonaponske energije, što predstavlja direktno pretvaranje sunčeve svetlosti u električnu energiju. Komercijalni fotonaponski materijali koji se koriste za fotonaponske sisteme obuhvataju solarne ćelije od silicijuma (Si), kadmijum telurida (CdTe), bakar idmijum diselenida (CIS) i solarne ćelije napraljene od drugih tankoslojnih materijala. U ovom radu se razmatraju različite tankoslojne fotonaponske tehnologije, trenutna situacija na tržištu i budući problemi koji budu nastajali sa povećanom potražnjom za fotonaponskom energijom. Takođe se ukazuje na prednosti tankoslojne fotonaponske tehnologije za integraciju u zgradama, zbog toga što tržište fotonaponskih ćelija integrisanih u zgradama i dalje predstavlja jednu od velikih nada za tankoslojne tehnologije.

Keywords: *tankoslojna fotonaponska; tehnologija; integracija u zgadi*

1. INTRODUCTION

One of the most promising renewable energy technologies is photovoltaic (PV) energy conversion. PV energy conversion represents the direct conversion of sunlight into electricity. Commercial PV materials commonly used for PV systems include solar cells of silicium (Si), cadmium-telluride (CdTe), coper-indium-diselenide (CIS) and solar cells made of other thin layer materials. PV systems are still an expensive option for producing electricity compared to other energy sources, but many countries support this technology. Over the last five years, the global PV industry has grown more than 40 % each year [1].

Starting from 1990 industry of photovoltaic conversion of solar irradiation shows constant annual economical growth of over 20 %, and from 1997 over 33 % annually. In 2000 total installed capacities worldwide have surpassed 1000 MW, and in developing countries have overreached more than million house-holds which are using electrical energy generated by means of the photovoltaic systems. It is predicted that PV will deliver about 345 GW by 2020 and 1081 GW by 2030. [2].

Silicon is a leading technology in making solar cell, due to its high efficiency. But many researchers, due to its high cost, are trying to find new technology to reduce the material cost for production of solar cells and thin film technology can be seen as a suitable substitution. However, the efficiency of solar cells based on this technology is still low, and researchers are intensively making an effort to enhance the efficiency. [3].

In this paper, it is analyzed the current status of the PV market and technology, and different thin film technologies, [4] based upon amorphous-silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide/copper indium selenide (CIGS/CIS), organic solar cells (OPV) and dye-sensitized solar cells (DSSC). It is expected that thin film PV technologies will play a main role in the world PV market in the near future. Further the advantages and perspective of the thin film photovoltaic technology for building integration are pointed out.

2. PV MARKET

Nowadays photovoltaics enjoy quick expansion in a market. Development of the PV market began between 1980 and 1990, encouraged by changes of the policy frameworks made in some of European and worldwide countries (Japan, Germany, etc). Today, the present PV market grows at very high rates, around 30 – 50 % per year, even higher. World PV production in 2009 increased to 10.66 GW (Fig. 1), [5].

PV applications are progressively finding their markets mainly in the United States, Japan, and the European Union (mostly Germany) and also in China and Taiwan. The annual production of PV cells and modules in the United States, Japan, European Union, and China/Taiwan in 2009 was 595 MW, 1.5 GW, 1.93 GW, and 5.19 GW, respectively. Recently, China/Taiwan became the leading PV country, and PV production has almost doubled. Another 6.9 GW of cell and 6.7 GW of module capacity are being added (in China, Taiwan, and Japan) bringing total global cell and module capacity to 25.1 GW and 22.7 GW, respectively [5]. This goal cannot be achieved on wafer Si only because of an expected Si shortage, despite a large annual production of semiconductor-purity Si, which is 30.000 tons/year. Therefore rapid infiltration of the thin film solar cells into the world PV market is necessary. [3,4].

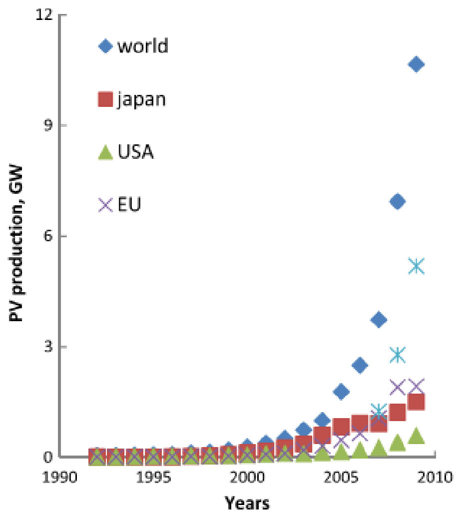


Fig. 1 Evolution of world PV cell/module production through 2009

Nowadays, over 80% of the world PV industry is based on c-Si and pc-Si wafer technologies, so these are the main materials for the world PV industry. The CdTe technology is growing sufficiently fast, while thin film CIGS and a-Si-based PV production is still in the beginning stages. It is expected that thin film PV technologies will play a major role in the world PV market in the near future. The main 10 producers of PV cells and modules are: First Solar, Suntech Power, Sharp, Q-Cells, Yingly Green Energy, JA Solar, Kyusera, Trina Solar, Sunpower and Gintech, with cell/module production in 2009 of 1.011 MW, 704 MW, 595 MW, 537 MW, 525 MW, 509 MW, 400 MW, 399 MW, 398 MW and 368 respectively. These companies totally produced 4.92 GW in 2009, which is arround 50 % of world production [5].

According to the European Photovoltaic Industry Association (EPIA), [6], the average price of a PV module in Europe in July 2011 reached around 1.2 €/Wp, which is about 70% lower than 10 years ago, and could further drop by 36–51 % by 2020. Forecasts suggest that the expense of producing modules for thin-film PV will fall to $0.50–0.70/Wp with system prices of $1.5– $2.5/Wp by 2020, assuming sufficient market incentives to maintain technology progress throughout this period. Each of the thin-film technologies has the potential to satisfy a 30–40 % per year overall PV growth, [7].

3. THIN FILM (TF) PHOTOVOLTAICS

Silicon is a leading technology in making solar cell due to its high efficiency. At the present, over 80% of the world PV industry is based on c-Si and pc-Si wafer technologies. However, due to its high cost, most researchers are trying to find new technology to reduce the material cost to produce solar cell and to till date, thin film technology can be seen as a suitable substitute, [4]. It is generally agreed that c-Si wafer technology would not be able to meet the low-cost targets, whereas thin-film technologies have the potential to provide a viable alternative in the near future.

Thin-film Si solar cells have few important advantages compared to crystalline cells: the thickness of Si can be drastically reduced to 50 µm, thin films can be deposited on low-cost substrates, thin films can be fabricated on module-sized substrates and in integrally interconnected structures, etc. Crystal-line Silicon on

Glass (CSG) is technology which involves the direct deposition of silicon onto glass and solid-phase crystallization for fabrication mini-module with efficiency of 8.0%, [3].

Three materials that have been given much attention under thin film technology are amorphous silicon, cadmium telluride/cadmium sulphide and copper indium gallium selenide/copper indium selenide, but researchers are continuously putting in more effort to enhance the efficiency. However, all of these materials have some bad impact on the environment. Another solution for thin film technology has been carried out by researchers by using polymer organic as a solar cell material. Polymer materials have many advantages like low cost, light weight and environmental friendly, but they have very low efficiency compared to other materials with just 4–5%, [4].

In this chapter, we will analyze current commercial and potential future TF PV technologies, with a special focus on their related prospective and challenging manufacturing issues.

3.1 Amorphous-silicon based PV

Commercial solar cell devices based on hydrogenated amorphous silicon (a-Si:H or a-Si) are typically made of a dual-junction with micro (μc-Si) or nano-crystalline (nc-Si) Si, (micromorph tandem), Fig. 2, [5,8].

The Si layers are deposited by plasma-enhanced chemical vapor deposition (PEC-VD) incorporating gaseous mixtures of H_2 and SiH_4. The design of the cells optimizes the collection of current by having very thin n- and p-layers, with an intrinsic intermediate layer, the thickness of which is enough to absorb almost all the incident light, to give a p-i-n structure, [8]. However, the physical properties of the i-layer degrade under illumination, because Si-H bonds are destroyed under visible light. This effect can be reduced (but not eliminated) by careful control of the deposition process, decreasing the thickness of i-layer, and using multiple junctions. As in the case for c-Si, a-Si technology was rapidly commercialized in the early 1980s.

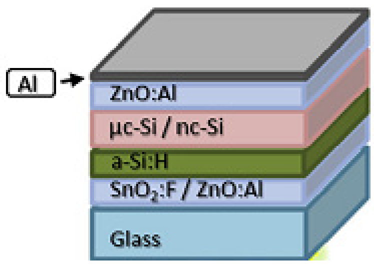


Fig. 2. Solar cell device based on a-Si/μ-Si

These devices rapidly surpassed 10% efficiency, but suffered from light-induced degradation that leads to a reduction of the solar cell efficiency. The possibility to deposit a-Si at temperatures below 200^0 enables the fabrication of light-weight, flexible laminates on temperature sensitive substrates, which is a unique feature that provides a competitive advantage in markets such as consumer products and BIPV, [5].

The best initial efficiencies of 13.7 % and 9.8 % were achieved on triple-junction cells and modules, respectively. However, stabilized efficiencies are still low, arround 6–7% for the best commercial modules. Nevertheless, at present, about 8–10% of the worldwide PV production uses a-Si technology, [3].

3.2 Cadmium-telluride

This material can produce high efficiency, more than 15 % and is also known to give an ideal bandgap (1.45 eV) since the direct absorption coefficient is very high.

A layer of cadmium sulphide is deposited from solution onto a glass sheet coated with a transparent conducting layer of thin oxide. Standard CdTe-based devices, comprising a glass substrate, the TCO, usually SnO_2:F (FTO) and/or $(In_2O_3)_{0.9}(SnO_2)_{0.1}$ (ITO), the n-type window layer (CdS), the p-type CdTe absorber, and finally the back contact (ZnTe/Cu/C or Mo), (Fig. 3), [5].

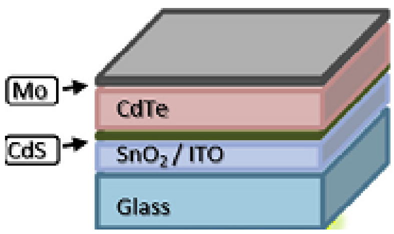


Fig. 3 Solar cell device based on CdTe

CdTe solar cells have been used for thin film photovoltaic applications since 1970. With the forbidden zone width of 1.5 eV and the coefficient of absorption 10^5 cm^{-1}, which means that a layer thickness of a few micrometers is sufficient to absorb 90 % of the incident photons, CdTe is almost an ideal material for solar cells manufacturing. CdTe solar cell is sensitive in the wave length of 0.3–0.95 mm and maximum of its sensitivity is in the wave length range of 0.7– 0.8 mm. Laboratory CdTe cells have the efficiency of 16 %, and commercial ones around 8 %. Great toxicity of tellure and its limited natural reserves decrease the prospective development and application of these cells, [4].

The key issues with respect to large-scale CdTe manufacturing are the abovementioned perceptions concerning Cd toxicity and Te availability. Testing of modules fate during fires or leaching of Cd from broken CdTe modules did not reveal non-neglibile threats to the human body or the environment so far, nevertheless module designs have been improved, [7]. The issue of Te availability will require substantial observation and fundamental research, whereas recycling may play a major role, not only regarding the toxicity of Cd but also regarding the reuse of Te, [5].

3.3 Copper–indium–gallium–selenide/sulphide

The first copper chalcopyrite PV devices were introduced in 1976 in the form of copper-indium-di-selenide ($CuInSe_2$ or CIS). Consequently, CIS, CIGS, CIGS or CIGSSe are generally used abbreviations to describe this material, depending on which and how many elements are involved. Its direct band gap can be as high as 1.68 eV with slight modification with Sulphur (S). The CIGSSe system with up to five elements and numerous binary and ternary phases, presents much greater complexity than the other commercial PV technologies, [5].

The basic structure of CIGS devices fabricated by current manufacturing schemes begins with the deposition of a Mo back contact followed by the p-type CIGS absorber (1–3µm), a thin buffer layer (50–100 nm), and a doped ZnO serving as the transparent front contact, Fig. 4.

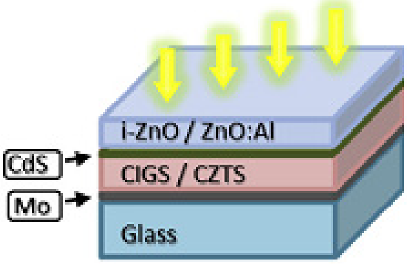


Fig. 4 Solar cell device based on CIGS/CZTS

CIGS is the only commercial TF technology that has continually reported efficiency improvements of its record cells during the last decade, with efficiency at present of 13 % for modules and 20 % for cell [9]. Today, several companies are producing commercial CIGS modules in the range of 10–50 MW/year with Japanese manufacturer Solar Frontier on the forefront selling 14.5% efficient modules from GW-scale production. Substrates include soda lime glass, metal foils, or high temperature polyimide that aroused substantial interest for BIPV and portable power applications, [5].

3.4 Organic solar cells

Single-junction OPV devices are generally comprised of a hetero-junction between an electron donor molecule (e.g. P3HT, poly 3-hexylthiophene) and an electron acceptor molecule (e.g. PCBM, phenyl-C61-butyric acid methyl ester) (Fig. 5) [5]. Similar to CIGS, OPV has made great leaps in terms of performance in the past decade, [10] with German company Heliatekbeing the first taking the 10% hurdle, reporting a 10.7% efficient organic tandem cell. Candidates for organic semiconductor materials may be categorized as either solution-processed (polymers, dendrimers, oligomers, or small molecules) or vacuum deposited (small molecules or oligomers).

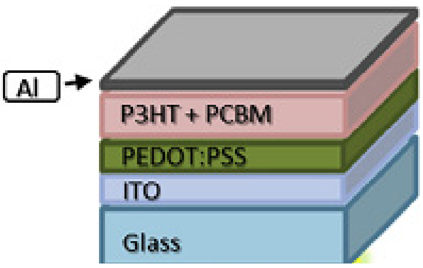


Fig. 5 Solar cell device based on OPV

Another main issue that has to be solved with organic solar cells is the stability regarding chemical, physical and mechanical degradation prime in organic materials and devices. Major issues include photo-degradation and the sensitivity to oxygen, requiring the use of ultra-barriers for encapsulation. Since organic PV (OPV) relies on carbon based semiconductors, low cost high volume manufacturing of flexible solar modules without any raw-material concern appears feasible [5].

3.5 Dye-sensitized solar cells

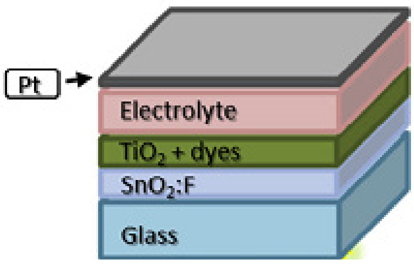


Fig. 6 Solar cell device based on DSSC

Due to some problems with efficiency, production cost and environmental related issues of some solar cell materials, researchers have come up with ideas to produce new material technology call dye-sensitized solar cell. Dye-sensitized solar cells (DSC or DSSC) were first introduced in 1991. A device is typically composed of organometallic dye molecules adsorbed to a mesoporous titania nanoparticle film, with the pore space filled by an electrolyte. In such a structure light is absorbed by the dyes injecting electrons into the TiO_2 network, which transports these to the front contact. If connected to an external load, the electrons return to the platinized back contact, where they reduce redox couples, which in turn diffuse through the electrolyte and regenerate dye molecules to complete the cycle (Fig. 6). The device is rapidly optimized the to more than 10% efficiency, a few years after of its introduction, [5].

In combination with the feature that devices can be fabricated in a number of colors and levels of transparency, this makes them an attractive applicant for BIPV applications. Fortunately, cell efficiencies are stagnant at about 11% since more than 15 years and further optimization of any main component of DSSC devices is not likely to yield significant efficiency improvements, [9].

4. PERSPECTIVE FOR THIN FILM PV USE

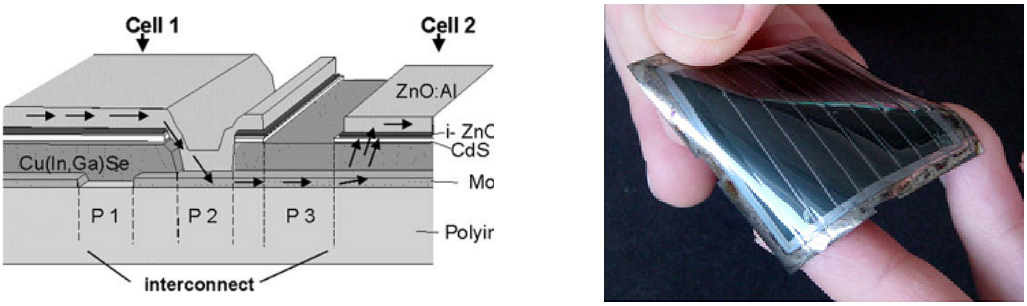
The Building integrated Photovoltaics (BIPV) market, which got increased political support during the last years is still one of the big hopes for TF technologies. In this context, these modules have many advantages compared to c-Si ones: strongly reduced weight for the application to the building stock, see through property, adjustable optical transmittance, excellent building appearance, potential capability for applying flexible substrates, and less sensitivity to the degradation of light intensity and increasing temperature of the module [11].

In perspective, new photovoltaic thin film will be the only technology suitable to satisfy the requirements of the most advanced architectural theories, and also the development of new photovoltaic thin film modules will be able to match not only traditional architectures, but also the most innovative tendencies that favour envelopes characterized by free morphologies.

Very important perspective of thin film PV technology is flexible modules with strategic space and military use, integration in roofs and buildings facades, etc. The ultimate advantage of thin-film technology is roll-to-roll manufacturing to produce monolithically interconnected solar modules leading to low time for energy payback because of high-throughput processing and to low cost of the overall system, [3,12].

Flexible a-Si solar cells are likely to be very popular and in demand for applications in the low to medium range of power, since they can be made in different shades (even semi-transparent), shapes, and sizes. Also, CdTe is one of the leading candidates for the solar cells due to its optimum band gap and the variety of film preparation methods. A large number of activities on highly efficient, stable, and flexible thin-film modules based on CIGS has recently drawn much interest for flexible solar cells on metal and plastic foils, [12]. Apart from the expected high efficiency and long-term stability for terrestrial applications, flexible CIGS has excellent potential for space application because of their tolerance to space radiation, being 2–4 times superior to conventional Si and GaAs cells. Flexible CIGS cells can be grown on polymide and on a variety of metals, e.g., stainless steel, Mo, and Ti, [3].

The basic schematic cross-section of a monolithic module on a polyimide substrate is shown in Fig. 7a, [12], and flexible prototype mini-module developed on polymer foil is shown in Fig. 7b. [3].



a) b)

Fig. 7. a) Patterning scheme for monolithic cell integration on a polyimide substrate
b) Flexible monolithic CIGS modules showing a prototype mini-module on a polymer foil

Table 1 gives an overview of different flexible solar cell technologies, including the organic and TiO_2 dye-sensitized PV technologies, [3]. High cell efficiency and inherent stability advantages indicate a promising potential for these technologies. The best thin-film CIGS module efficiency is 11.0%.

Another advantage of flexible solar cells, and maybe the most important one, is the potential to reduce production costs.

5. CONCLUSION

In this paper the current commercial and potential future of TF PV technologies is analyzed, with a special focus on their related prospective and challenging manufacturing issues. Commercial c-Si cells have efficiencies in the range of 15–22%, so any TF PV still have to compete with this technology. Also TF PV will also have to make use of its potential advantages, such as reduced use of material, larger production units, and integrated cell/module fabrication, and particularly the application of thin, flexible and lightweight substrates. The use of flexible substrates offers new possibilities for the application of solar cells, for example for building integration. In addition, flexible cells are very thin and lightweight, which makes them also more flexible in use than rigid cells. One of the most important advantage of flexible solar cells, is the potential to reduce production costs. Development of photovoltaic thin film modules ensures a satisfying flexibility of the surface, and the possibility to design appropriate shapes. The future for efficient, lightweight, flexible and cost-effective thin film modules looks very promising.

Table 1. Overview of different flexible solar cell technologies.

	CIGS	CdTe	Amorphous silicon	Organic and titanium oxide
Lab efficiency on plastic foil	14.1% (single-junction cell)	11.4% (singlejunction cell)	8%*–12%* (multi-junction cell) 5	5–8%
Lab efficiency on metal foil	17.5% (single-junction cell)	8% (single-junction cell)	14.6% /13%* (multi-junction cell)	
Industrial efficiency (typical values)	6–11% (On steel foil, not yet available on plastic foil)	Not yet demonstrated	4–8% * (available on plastic and metal foils	Not yet demonstrated
Stability under light	Material stable	Material stable	Degrades	Stability not proven

*Initial values measured before light-induced degradation of solar cells.

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