

CONFIGURATION OF THIN-FILM PHOTOVOLTAIC CELLS

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ABSTRACT

This paper discusses configuration of thin-film photovoltaic cells, which are one of the new trends in the sphere of solar system. The first part of the paper is very shortly introduction to problematic of the Sun energy and its utilization in the sphere of photovoltaic. The basic information of the Sun, its energy, the photovoltaic effect and the photovoltaic cells are presented here. Problematic of the thin-film photovoltaic is analyzed in the second part. At the beginning of this part term “thin film” is defined. Then three basic configurations of the thin-film cells (superstrate, substrate and tandem) are distinguished. Principle, sequences of thin layer and materials two of these configurations are briefly mentioned in this part among others.

KEYWORDS

Photovoltaic, thin-film photovoltaic cells, tandem cells, silicon

1. INTRODUCTION

Concern over global climate changes, air pollution and resource energy scarcity make the photovoltaic (abbr PV) very increasingly attractive energy supply technology (growing c. 33%/yr). Unfortunately, contemporaneous PV technology based on the crystalline silicon wafers (PV cells 1st generation) has few disadvantages – e.g. high power and financial intensity of production, lower efficiency during diffused solar radiation, considerable consumption of materials, indirect semiconductor material, and high energy pay back time, expensiveness, etc. As a result, research in this sphere is progressing on finding of material in effort to improve the PV cells performances, decrease production intensity, and reduce cost and consumption of material.

The thin-film (TF) materials offer promising alternative to crystalline silicon technology, which have dominated the evolution of PV technologies since its origins (note: currently, crystalline silicon cells rank 82% of market share). Configuration of thin-film photovoltaic cells (PV cells 2nd generation) is different compared to crystalline silicon (c-Si) cells. Instead p-n junction, thin-film cells use p-i-n junction, which consist of p-doped, un-doped and n-doped layer. Photovoltaic cells from thin-film materials have few advantages. Due to these advantages it can be supposed, that thin film will become the very important PV material in the future.

2. SOLAR ENERGY AND POSSIBILITIES ITS UTILIZATION

2.1. Solar Energy as Renewable Energy Source

The Sun is the biggest and the most important star of our Galaxy, which originated from supernova the Geminga 4,75 milliards years ago. It concerns huge plasma ball energy radiating. This electromagnetic radiation, which is necessary anticipation of live on the Earth, treats as the renewable energy source. Energy is profited by fusion reaction in nucleus of the Sun – 560 millions tons of hydrogen converts into 556 tons of helium each second, other 4 millions tons of hydrogen converts into two energy types:

electron neutrinos and electromagnetic radiation. Particles of this radiation, so called the photons, diffuse towards surface of the Sun, from where advance to the Earth, where it is applied.

There are two possibilities to exploit solar radiation. The solar technologies are characterized as either passive or active depending on way how they capture, convert and distribute energy. Active solar technologies include PV cells and solar thermal collectors. Passive technologies include e.g. orientation of buildings to the Sun and selecting suitable materials with favourable properties. Passive utilization of solar energy is older. The Sun has influenced building design since architectural starting.

2.2. Photovoltaic Effect and Photovoltaic Cells

In spite of, the people have derived benefit from solar energy since ancient times; research in this sphere began as late as the 16th century, when first solar systems were generated. Breakage in research works came but as late as the 19th century, when French physicist A. E. Becquerel discovered the photoelectric effect – headstone of photovoltaic. This effect can be defined by physical effect, when electrons are emitted from material in consequence of its absorption of solar radiation.

Devices, which are used to derive benefit from this effect by converting solar energy into electric power, are named “photovoltaic cells”. First PV cell using semiconductor silicon p-n junction was developed in the Bell Labs in the United States of America in 1954. Its efficiency achieved 6 % and basic material was c-Si. Unfortunately, c-Si isn't too suitable material for photovoltaic cells. It has few disadvantages, as mentioned earlier. For this reason, research in this sphere is progressing on finding new better PV technologies or materials.

3. THIN-FILM PHOTOVOLTAIC CELLS

3.1. Briefly Introduction to Thin-Film Photovoltaic

“Thin-film” is term used for material layer ranging of nanometers to several micrometers in thickness, which is applied on the substrates (e.g. glass, stainless steel, plastic foil). Resulting thin-film material is composed of single thin film, substrate and interface between thin film and substrate. The act of applying thin-film is so called deposition. The deposition methods divide into two groups depending on whether processes are mainly – chemical vapor deposition or physical vapor deposition. In these ways prepared thin layer have special properties that destine these films for various utilizations – e.g. power and mechanical engineering, medicine or thin-film photovoltaic.

The thin-film PV cells are PV cells produced by deposition one or more thin-layer material on substrate.

3.2. Configuration of Thin-Film Photovoltaic Cells

Design of thin-film PV cells is completely different compared to PV cells 1st generation. There are two typical configurations of thin-film cells – the substrate configuration and the superstrate configuration (see Fig. 1). These configurations differ in sequence of individual thin layers. Thin layer of superstrate configuration are deposited on substrate in direction from light-exposed to shaded side; in the case of substrate configuration structure it is opposite.

Instead of the p-n junction used in c-Si PV cells, thin-film cells use the p-i-n junction or the heterojunction. p-i-n junction consists of p-doped, un-doped and n-doped layers of semiconductor materials. Un-doped so called the intrinsic layer (i-layer) plays the most important role – this layer is single PV active layer. It means that it is able to absorb incident electromagnetic Sun energy and to generate electron-hole pairs, which enhance electric conductivity. Due to i-layer is often named the absorber layer or the photo generation layer.

In this context, such intrinsic layer must meet three following requirements. It must possess sufficiently high value of optical absorption coefficient in useful spectral range of solar radiation and high value of product of high mobility multiplied by lifetime for charge carrier. Besides it must allow for high and uniform internal electric field. This field between p-layer and n-layer ensure separation of electron-hole pairs as with c-Si cells. Big problems are dangling bonds (i.e. charged defects) and band tails states, which cause the effect no uniformity (see Fig. 2).

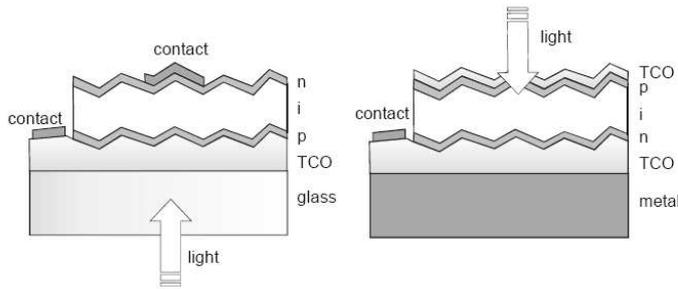


Fig. 1 – Layers sequence of various configurations (left: superstrate, right: substrate configuration)

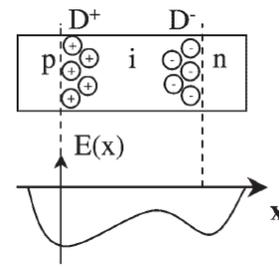
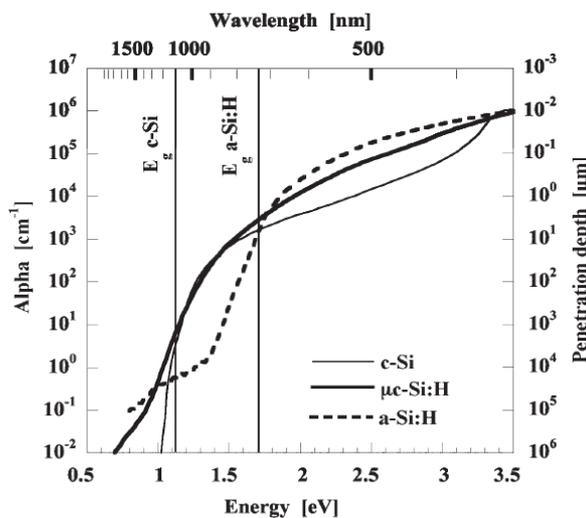


Fig. 2 – Schematic representation of deformation of internal electric fields due to charged defects

Graph 1 shows the optical absorption coefficient “alpha” as function of the photon energy for three different PV materials. Vertical axis of this graph is calibrated in so called penetration depth (i.e. layer thickness, within which 63% of incident photons is absorbed). Graph points very important crossover point between hydrogenated amorphous silicon (a-Si:H) and hydrogenated microcrystalline ($\mu\text{c-Si:H}$) silicon, which is around 1,75 eV. For energy above 1,75 eV, a-Si:H layers have higher value of absorption coefficient. For energy below 1,75 eV, $\mu\text{c-Si:H}$ layer have higher coefficient. This fact indicates that it could be very advantageous to use a-Si:H and $\mu\text{c-Si:H}$ jointly within the tandem configuration PV cell, i.e. tandem cell is PV cell used a-Si:H along with $\mu\text{c-Si:H}$ (see Fig. 3).



Graph 1 – Optical absorption coefficient as function of photon energy for three different silicon forms

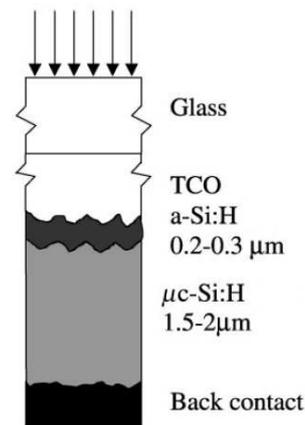


Fig. 3 – Layers sequence of tandem configuration

3.3. Superstrate Configuration

The superstrate configuration is first of configurations of thin-film PV cells. Thin layers of this configuration deposit on the substrate in the direction from light-exposed side to shaded side. The light enters the cell through substrate, on which the transparent conductive oxide (TCO) layer about thickness c. 600 nm is deposited as contact. The p-layer is deposited as the first part of semiconductor junction on the top of glass-TCO combination. This layer is first crossed by incident electromagnetic solar radiation. For this reason, it should be relatively thin (c. 10 nm) and have low value of absorption coefficient. Then the radiation crosses thicker i-layer and thin n-layer (c. 20 nm). Lastly it reaches TCO as second contact.

Briefly: This configuration starts with substrate and TCO as rear contact and subsequently layers sequence (junction) consisting of semiconductor materials and lastly again TCO as front contact – i.e. to basic materials used in superstrate configuration belongs material of semiconductor junction, TCO and substrate.

Materials of Semiconductor Junctions

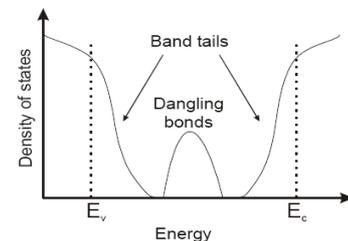
The superstrate configurations often use for create junctions two following semiconductor materials – hydrogenated amorphous silicon and cadmium telluride (CdTe). First mentioned, a-Si:H, is described for more detail in this paper.

Amorphous silicon (a-Si) is the non-crystalline form of silicon, which possesses short-range atom structure in comparison to c-Si. Similarity of the covalent bonds between the silicon atoms in c-Si and a-Si, similarity of the same number of neighbours and the same average bond lengths and angles leads to similar electronic structure – amorphous and crystalline silicon form have comparable band gaps. That is way a-Si is semiconductor material as well as c-Si. First information about potential utilization of a-Si in PV cells appeared forty years ago, when it was discovered, that a-Si has semiconductor properties. Unfortunately, shortly after this discovers other very important fact was detected – due to the disorder structure of a-Si the dangling bonds are created simply (e.g. by radiation or temperature).

Physically, the dangling bonds are charged defects lying in the band gap (see Graph 2), which cause unusual unwelcome electrical properties. Researches understood, that high dangling bonds density in a-Si prevented this material from being useful for PV applications and tried to find ways to eliminate these defects. It was found to be passivation by hydrogen favourable. Hydrogen atoms bond to dangling bonds thereby reduce their density. Import role of hydrogen in a-Si structure was recognized at the Harvard University in the late 1960s. Local researchers found out, that material properties are improved by addition of 10% hydrogen atoms into amorphous structure. Hydrogen passivated a-Si, so called hydrogenated amorphous silicon, was first made in the United Kingdom. This material was first applied as material for PV in the mid 1970s, when the substrate configuration was introduced at RCA Labs in New Jersey.

Efficiency of this PV cell was very small, about 2%. Nevertheless a-Si:H has used in PV cell since this time. Currently, efficiency obtains 10% in lab conditions. However, cells from this material suffer from the light-induced effect (so called Staebler-Wronski effect), which cut efficiency. This effect is along with big necessary area for installation 1 kWp (about 15 m²) the biggest disadvantages of photovoltaic cells from a-Si:H.

a-Si:H is can be directly derived from decomposed the gas silane (formula SiH₄) at relative low temperature (from 80 to 200°C) by the plasma enhance chemical vapour deposition (PECVD). It is the deposition utilizing RF (13,56 MHz) glow discharge incipient between two electrodes, in which silane is decomposed. Elements incurred during decomposition migrate onto substrate, where thin film growths. That was intrinsic layers are created. Doped layers are made addition of dopants (phosphine and diborane). Interestingly, the deposition rate is low. This leads to long deposition time, e.g. 50 minutes for 0,3 µm thickness layers.



Graph 2 – Density of states as function of energy

Second material used in this cells configuration for creating of junction is CdTe – polycrystalline semiconductor material. Thin-film PV cells from CdTe have been investigated the longest of all thin-film PV materials. These PV cells use heterojunction cadmium telluride/cadmium sulphide (CdTe/CdS). Interestingly, most often one contact is made from TCO and second from carbon paste with cooper (Cu, it isn't TCO as in the case of a-Si:H cells).

Briefly: superstrate configuration of CdTe PV cells can be described in this manner: glass/TCO/CdS/CdTe/Cu. Note: cadmium is carcinogen. That is why European Commission solved utilization of this material in thin-film cells few months ago. As a result, CdTe can be used in thin-film PV cells (the commission gave the exception to the Restriction of the use of Hazardous Substances).

Transparent Conductive Oxides

The transparent conductive oxides are generally used for the contacts of all configurations of thin-film PV cells. These semiconductor materials compound of the metallic oxide have special properties (mainly electrical and optical) – e.g. wide optical band gap, high transparency in visible range of solar spectrum, high value of absorption coefficient or low value of sheet resistance. TCO for utilization in the thin-film PV sphere should meet few requirements: e.g. carrier concentration easily 10²⁰ cm⁻³, low resistivity (between 10⁻⁵ and 10⁻⁴ Ωcm), wide band gap (c. 3,4 eV), etc. These requirements zinc oxide

and indium tin oxide (ITO) meet very well. However, ITO has very big disadvantage – expensiveness. Indium is rare metal with bright luster (in the Earth crust is more than three times abundant as silver). Due to cost of indium is very high (c. \$700 per 1 kilogram). For this reason, zinc oxide (aluminum-doped zinc oxide or gallium-doped zinc oxide) is most widely used TCO in all of thin-film PV cells.

Zinc oxide layer can be obtained by few deposition methods. Layer quality, homogeneity, cost, availability and needed equipments are determining choice of deposition technique. Most widely used deposition method RF magnetron sputtering is. It is deposition technique utilizing high energy of ions, which are generated in argon gas using alternating power at the frequency about 13,56 MHz between two electrodes long distance 110 nm. These ions bombard the target (zinc oxide + aluminium oxide) out of it release atoms. Ions lose their energy during individual collision with target atoms and eject atoms from target. These ejected atoms migrate onto substrate, where condense and create thin film.

Substrates

The substrate of superstrate configuration is most often glass (type of glass is not too important).

3.4. Substrate Configuration

The substrate configuration is second of most often-used thin-film PV cells configurations. In this case, the layers are deposited in opposite sequence as in the case of superstrate configuration – i.e. in the direction from shaded side to light-exposed side. The solar radiation enters the cell through layer of TCO on which three layer of semiconductor junction deposit. As first semiconductor layer n-layer is deposited on top of TCO. Incident light first crosses this layer. Due to n-layer should be thin as well as p-layer in the case of first mentioned configuration. Subsequently the light crosses thicker i-layer, thin p-layer and reaches TCO. All of these layers are deposited on substrate.

Briefly: First part of substrate configuration is TCO as front contact. Second part is semiconductor junction and in consequence TCO as rear contact – i.e. this configuration uses the same materials as superstrate configuration: material of semiconductor junction, TCO and substrate.

Materials of Semiconductor Junctions

p-i-n junctions in cells with substrate configuration are made from a-Si:H and copper-indium-gallium-diselenid (CIGS).

In this time, thin-film cells based on CIGS achieve the highest efficiency of all thin-films PV cells (20,3%, August 2010, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg in Germany, lab conditions). As well as CdTe cells CIGS cells use heterojunction. These cells have heterojunction CIGS/CdS. One of contacts is made from TCO and second from molybdenum (Mo).

Briefly: substrate configuration of CIGS PV cells can be characterized in this manner: TCO/CdS/CIGS/Mo/substrate.

Transparent Conductive Oxide

This configuration uses the same transparent conductive oxide as superstrate configuration – i.e. zinc oxide (see chapter 3.3, part “Transparent Conductive Oxide”).

Substrate

Beside glass (mainly soda-lime glass), substrate configuration use stainless steel and plastic foils – i.e. thin-film PV cells having this configuration are suitable for building-integrated photovoltaic (BIPV, e.g. roofs, facades) due to their big flexibility.

4. CONCLUSIONS

Problems of the PV cells becomes more and more topical in the connection with increasing demand after energies, sharply rising cost of energies, resource energy scarcity and environment protection. For these reasons, new technologies of cells are developed. This paper is focused on one of the new trends in the PV sphere – on the thin-film PV cells.

Thin-film materials constitute at the present time one of the most promising PV technology for following advantages – e.g. lower power and financial intensity of cell production, lower consumption of material, abundant and non-toxically material, direct band gap, utilization in sphere of buildings

integrated PV, higher efficiency during diffused radiation, lower energy pay back time, lower cost, etc. Unfortunately, thin-film PV cells have three disadvantages – lower total efficiency in comparison with c-Si PV cells, higher necessary area for installation 1 kWp in comparison with c-Si cells and the light induced degradation. In spite of, it supposes, that thin-film PV cells will become important power technology in the future.

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