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Materials for solar cells - state of the art and perspectives

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The present paper is dedicated to photovoltaic (PV) materials. First the principle of photovoltaic effect is examined. Then an overview of materials currently being used in solar cells and discussion of their development in future is presented. Problems related to the implementation of new material in solar cells are also addressed.

1. INTRODUCTION

At the heart of every solar cell is a semiconductor. A standard p-n semiconducting junction of respectively large area constitutes a single PV cell. When such a junction is established, free electrons and holes do mix and form a barrier, making it harder and harder for electrons on the n side to cross to the p side. Eventually, equilibrium is reached, and we have an electric field separating the two sides. This electric field acts as a diode, allowing electrons to flow from the p side to the n side, but not the other way around.

2. PHOTOVOLTAIC EFFECT AND STRUCTURE OF SOLAR CELL

The conversion of light energy into the electric one occurs during attacking a semiconductor p-n junction by a flow of photons. Basically, when photons (light) strike the PV cell, a certain portion of them is absorbed within the semiconductor material. Absorbed photons of sufficient energy knocks electrons loose, allowing them to flow freely. As a result, inside the semiconductor appear redundant charge carriers i.e. electron-hole pairs. From the energy conversion point of view photons having enough energy to form electron-hole pairs are important. In order to dislodge an electron from its covalent bond and make him free photon energy must be at least as high as the band gap energy (E_g) of semiconductor. The band gap energy, measured in electron volts (eV), is a characteristic parameter of semiconductor. As it was mentioned in introduction PV cells have electric field in the junction area that act to force electrons and holes freed by light absorption to flow in opposite directions. Electrons flow to n-type layer and holes to p-type layer. This flow is a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to use externally. This current, together with the cell's voltage, defines the power that the solar cell can produce.

The question is why can't we choose a material with a really low band gap, so more of the photons be able to form an electron-hole pairs? Unfortunately, the band gap also determines the other parameters of PV cell. The smaller is band gap energy the smaller is open circuit

voltage and higher short circuit current. On the other hand, the higher is band gap energy the higher is open circuit voltage and smaller short circuit current. Don't forget that power is voltage times current. The optimal band gap, balancing these two effects, ranges from 1.3 to 1.6 (eV) for a cell made from a single material (Fig. 1). That's because this level of energy is good for freeing electrons without causing extra heat and optimal light to electric energy conversion efficiency. Conversion efficiency is defined as a ration of maximum electric energy power to illuminating light power. It determines effectiveness of light to electric energy conversion.

Typical solar cell is a multi-layer device (Fig. 2). Basically, it consists of two layers made of **n-type** and **p-type** semiconducting material. It is the heart of solar cell where photovoltaic effect takes place. Two very essential parts of a PV cell are the electrical contacts, because they are the bridges that connect the active semiconductor to the external load. The **back contact** of a cell is relatively simple and usually consists of a layer of aluminium or molybdenum. But the front contact is more complicated. When placed in sunlight, the cell generates current all over its surface. Attaching contacts just at the edges of a cell would not be adequate because of the excessive electrical resistance of the top layer in this configuration. So, the contacts must be made across the entire surface to collect the most current. This is normally done with a metal grid. Unfortunately, placing a large grid on the top of the cell shades the active parts of the cell from the sun, effectively reducing the cell's conversion efficiency. Therefore, in designing **grid contacts**, we must balance electrical resistance losses against shading effects. The usual approach is to design grids with many thin, conductive fingers spreading to every part of the cell's surface. Such a grid keeps resistance losses sufficiently low, while shading only about 3% to 5% of the active surface.

Semiconductors in PV cells happens to be a very shiny material, which means that it is very reflective. Photons that are reflected can't be used by the cell. For that reason, an **antireflective coating** is applied to top of the cell to reduce reflection losses to less than 5 %.

On top of the complete cell typically a **glass cover** or other type of transparent encapsulant is added to seal the cell and keep weather out.

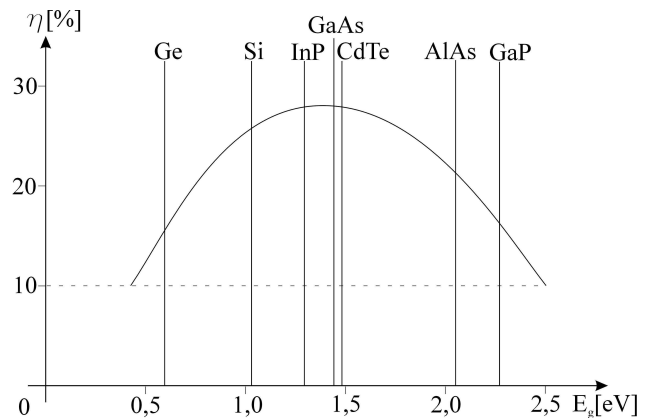
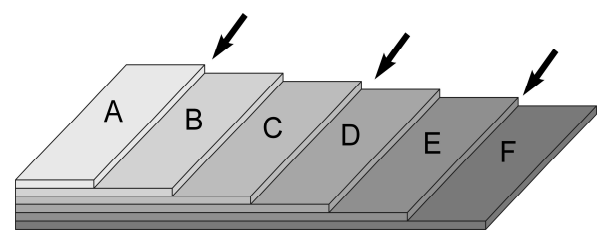


Fig. 1 Maximum theoretical conversion efficiency versus band gap energy



A - cover glass C - contact grid E - p-type Si
B - antireflective coating D - n-type Si F - back contact

Fig. 2 Basic structure of a silicon PV cell

3. MATERIALS IN PV CELLS – PRESENT STATUS

The most important parts of a solar cell are the semiconductors' layers, because this is where the electron current is created. There are a number of different materials suitable for making these semiconducting layers, and each has benefits and drawbacks. Unfortunately,

there is no one ideal material for all types of cells and applications. At present, there are available on market PV cells made of the following semiconductors:

- thick crystalline sliced from boules or castings
 - monocrystalline silicon (mc-Si),
 - polycrystalline silicon (pc-Si) ,
 - crystalline gallium arsenide (GaAs),
- thin-film (deposited in thin layers on a substrate) polycrystalline or amorphous
 - hydrogenated amorphous silicon (a-Si:H),
 - crystalline cadmium telluride (CdTe),
 - crystalline cooper-indium diselenide (CuInSe₂).

At present the industry is investing worldwide mainly in the materials specified above. In the sequel, we discuss in detail each of them.

3.1 Crystalline silicon (c-Si)

Crystalline silicon is currently the dominant solar-cell material for commercial applications because it is so readily abundant. Thus, the availability of raw material is a significant advantage of this technology. However, to be useful in solar cells, it must be refined to 99.9999% purity. This factor increase considerably production costs of crystalline silicon based solar cells.

At present, there are available on market solar cells made of both mono and polycrystalline silicon. The present total market share of crystalline silicon PV cells is about 82%.

In monocrystalline silicon, the molecular structure of the material is uniform because the entire structure is grown from the same single crystal. In other words, material is structurally uniform, i.e. there are no disturbances in the orderly arrangement of atoms. This uniformity is ideal for efficiently transferring electrons through the material. Currently, there are available on the market mc-Si solar cells whose conversion efficiency ranges from 15% to 20% [7].

Polycrystalline silicon, on the other hand, consists of several smaller crystals called grains having different crystallographic orientation, which introduce boundaries. Grains boundaries impede the flow of electrons and encourage them to recombine with holes rather than contribute to the electrical current and thereby reduce the power output of the cell. Thus the efficiency of pc-Si PV cells available on the market is 10% to 14% and it is slightly lower than that of mc-Si [1]. Generally, mc-Si PV cells have higher efficiency than that of pc-Si, but on the other hand they have also higher production costs. Their advantage is flexibility, suppleness to mechanical stresses. It is believed that c-Si technology will maintain a major market position for at least another 10 years.

3.2 Crystalline gallium arsenide (GaAs)

Gallium arsenide (GaAs) is a compound semiconductor: a mixture of two elements, gallium (Ga) and arsenic (As). Gallium is a byproduct of the smelting of other metals, notably aluminum and zinc, and it is rarer than gold. Arsenic is not rare, but it is poisonous. The following properties make GaAs especially suitable for use in solar cells [3]:

- The GaAs band gap is 1.43 eV, nearly ideal for single-junction solar cells (Fig.1).
- The GaAs has high charge carriers mobility, over 4-times better compared to c-Si.
- GaAs has an absorptivity so high it requires a cell only a few microns thick to absorb sunlight. Crystalline silicon requires a layer 100 μm or more in thickness.
- Unlike silicon cells, GaAs cells are relatively insensitive to heat. Cells can operate in quite high temperatures.

- Alloys made from GaAs using aluminium, phosphorus, antimony, or indium have characteristics complementary to those of gallium arsenide, allowing great flexibility in cell design.
- GaAs is very resistant to radiation damage.

GaAs solar cells have the highest efficiency of all commercially available cells, which exceeds even 30%. The greatest barrier to the success of GaAs cells has been the high production costs of a crystalline GaAs. That is why GaAs solar cells find application in a very specific fields especially where high efficiency is required, e.g. they are employed as a power generators in orbiting space stations and space shuttles. To be cost-effective for terrestrial use, GaAs high-efficiency cells are used primarily in concentrator systems. In this configuration, the cost is low enough to make GaAs cells competitive, assuming that module efficiencies can reach between 25% and 30%.

3.3 Amorphous silicon (a-Si:H)

Amorphous solids are materials in which the atoms are not arranged in any particular order. They do not form crystalline structures at all, and they contain large numbers of structural and bonding defects. Amorphous silicon absorbs solar radiation 40 times more efficiently than does crystalline silicon, so a film only about 1 μm thick can absorb 90% of the usable solar energy. This is one of the most important factors affecting its potential for low cost production. Other principal economic advantages are that amorphous silicon can be produced at a lower temperature. These characteristics make amorphous silicon the leading thin-film PV material. Because amorphous silicon does not have the structural uniformity of crystalline or even polycrystalline silicon, the small deviations result in defects such as dangling bonds, where atoms are missing a neighbour to which they can bond. These defects provide places for electrons to recombine with holes rather than contributing to the electrical current. Ordinarily, such a material would be unacceptable for electronic devices because the defects limit the flow of current. But if amorphous silicon is deposited in such a way that it contains a small amount of hydrogen, then the hydrogen atoms combine chemically with many of the dangling bonds, essentially removing them and thereby permitting electrons to move through the amorphous silicon. Typically, a-Si:H contains between 8% to 12% of hydrogen.

Amorphous silicon is the only thin-film technology that has a substantial market share (about 13%) and it is generally believed to be the first thin-film technology that competes with c-Si. Moreover, unlike c-Si, a-Si:H is produced in the thin-film technology avoiding material losses for sawing and polishing. As a result, production costs of a-Si:H solar cells are significantly lower. Solar cells based on a-Si:H available on the market have conversion efficiency of 10% [1].

The thin-film a-Si:H based solar cells suffer specific losses in performance due to fundamental material changes. This degradation in a-Si:H cells is known as a photodegradation or Staebler-Wronski effect [8]. The degradation takes place predominantly in the first month of sunlight exposure, whereas it becomes negligible later on. It is essential drawback of a-Si:H cells.

3.4 Cadmium telluride (CdTe)

Cadmium telluride is another prominent polycrystalline thin-film material. It is a material very easy to make with almost ideal band gap energy (1.44 eV). CdTe also has a very high absorptivity. Currently CdTe is at the point of first production. The present total market share of cadmium telluride is about 1%. The only problem may be caused by the possible toxicity of CdTe with respect to use of Cd, especially in relation to legislation related to environmental protection. In many developed countries, this legislation prohibits the

production of and trade in products containing cadmium. CdTe solar cells have efficiency between 10% to 12% and hold the promise of low cost production [2]. The toxicity and availability of raw material are the main drawbacks of CdTe technology.

3.5 Cooper-indium diselenide (CuInSe₂)

At present, CuInSe₂ is at the point of the first pilot-production. Many industrial groups worldwide are investigating it. Commercial CuInSe₂ solar cells have entered the market (Siemens Solar) with top efficiencies of over 11% [5]. CuInSe₂ has an extremely high absorptivity that allows 99% of the available light to be absorbed in the first micron of the material. CuInSe₂ is the only thin-film material with several years of outdoor exposure that shows no deterioration in performance. Adding small amounts of gallium to the absorbing CuInSe₂ layer boosts its band gap (from its normal 1.0 eV), which improves the voltage and therefore the efficiency of the device. The advantage of CuInSe₂ cells is relatively simple production technologies. However, the availability of raw material is an important issue. Researchers studying this technology have difficulty avoiding defects that prevent the formation of uniform layers.

4. FUTURE PROSPECT FOR SOLAR CELLS

This section is devoted to study possibilities of development of PV systems in future. It is expected that research in PV technology will be directed in future towards the following issues:

Polycrystalline thin films technology

It is believed that thin films technology has great potential for the PV industry. Polycrystalline thin-film devices require very little semiconductor material and have the added advantage of being easy to manufacture. In this technology, we sequentially deposit thin layers of the required materials, rather than growing, slicing, and treating a crystalline ingot (required for crystalline silicon). Several different deposition techniques are available, and all of them are potentially cheaper than the ingot-growth techniques required for crystalline silicon. Best of all, these deposition processes can be scaled up easily so that the same technique used to make small laboratory cells can be used to make industrial module of huge area. Consequently, solar power is getting cheaper and consumption is increasing. Experts predict that thin films technology will deliver highly efficient solar cells at one-quarter to one-fifth the cost of today's cells.

Heterojunction solar cells

Polycrystalline thin-film cells comprise of many tiny crystalline grains of semiconductor materials. The materials used in polycrystalline thin-film cells have properties that are different from those of silicon, so it has proven to be better to create the electric field with an interface between two different semiconductor materials. This type of cell is referred to as a heterojunction. The typical polycrystalline thin film has a very thin (less than 0.1 μm) layer on top called the window layer. The window layer's role is to absorb light energy from only the high-energy end of the sun's spectrum. It must be thin enough and have a wide enough band gap energy (2.8 eV or more) to let all the available light pass through the interface (heterojunction) to the absorbing layer. The absorbing layer under the window, usually doped p-type, has a high absorptivity to produce high current and a suitable band gap to provide a good voltage. Still, it is typically just 1 to 2 μm thick.

Multijunction (tandem) solar cells

Today's most common PV devices use a single junction, to create an electric field within a semiconductor. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit. One way to

get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as multijunction or tandem cells. A multijunction PV cell is stack of individual single-junction cells in descending order of their band gap energy. Sunlight then falls first on the material with the largest band gap, and the highest-energy photons are absorbed. Photons not absorbed in the first cell continue on to the second cell, which absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons.

Organic/Polymeric solar cells

At present, organic solar cells are a set of several different technologies, ranging from the well-known dye-sensitised solar cells via molecular organic solar cells to completely polymeric cells. It is believed that, the dye solar cells are closest to market introduction.

The main problem with organic solar cells is their stability. When exposed to the light, working temperatures can be high, which can induce mechanical stress. Also, organic solvents are generally not very stable in light and the presence of so many electrons can initiate decomposition reactions. So, fundamental research has to be done and huge improvement in terms of stability and efficiency must be made in order to develop these promising cells. Expert believe that the efficiency of organic cells will be relatively low compared to others technologies in the short term. In a long term, due to molecular engineering and advanced cells concepts the highest efficiencies are foreseen.

5. CONCLUDING REMARKS

An intensive development of the photovoltaic techniques becomes an indisputable necessity facing diminishing resources of energy. Photovoltaics seems to be the most promising new electric energy source. What is needed to transform solar power from a marginalized technology to a mainstream source of energy is cheaper materials. At present, the main scientific effort is made to lower production costs of PV systems and improve their parameters. It is believed that in the not so far future thanks to new materials, solar cells could be ubiquitous and one of the cleanest energy sources all over the world.

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