

6. Photovoltaic cell types

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Learning Outcomes

- Get a picture of the evolution of global photovoltaic production
- Understand the concept of solid crystallized materials
- Figure out the difference of mono- and polycrystalline silicon solar cell
- Understand the concept of amorphous and thin film materials
- Recognize the structure of CdTe and CISG thin film cells as well as amorphous Si-cells
- Work out the mainstream photovoltaic technologies
- Get the picture of emerging photovoltaic technologies

Introduction

Worldwide solar photovoltaic (PV) capacity will reach 320 to 430GW by the end of 2018. Fig. 1 shows a global cumulative scenario of the PV market [1]. The low end assumes that new markets in emerging countries will fail to take off, while the upper end assumes a robust PV market in emerging regions [2].

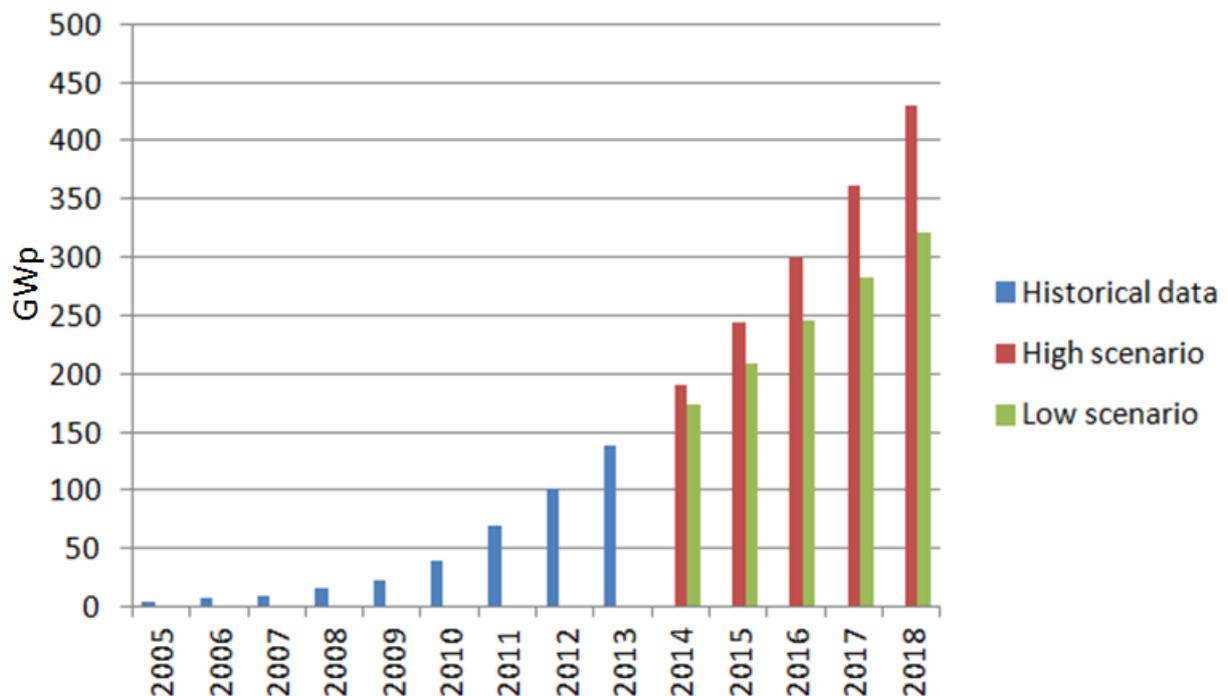


Fig. 1 Global PV cumulative scenario until 2018, data from [1]

For the production of solar panels, we can distinguish two mainstream technologies:

- Solid crystallized materials
- Amorphous and thin film materials

The first category (Solid crystallized materials) represents about 90% of the market share, where as amorphous and thin film materials cover the remaining 10%, but with an increasing trend.

There are also emerging technologies such as:

- Grätzel photoelectrochemical solar cells
- Organic solar cells

These emerging PV cells are not yet mature for large-scale production and installation; but their promising properties make them serious candidates for the PV market in the coming years.

Solid crystallized materials

Monocrystalline Silicon

The monocrystalline silicon solar cell is made of a large single crystal of pure silicon. This single crystal is mostly fabricated owing to the Czochralski method. It consists of melting high-purity, semiconductor-grade silicon having only a few parts per million of impurities in a crucible at 1425 degree Celsius. During this melting process, dopant impurity atoms such as boron (for p-type semiconductor) or phosphorus (for n-type semiconductor) are added to the molten silicon to dope the silicon; for PV-cells the preferred dopant is boron. The second step consists to dip a rod-mounted seed crystal into the molten silicon. The seed crystal has a well-defined crystal orientation. Next, the crystal's rod is carefully pulled out and rotated simultaneously. The temperature gradients, the pulling-rate and the rotation speed must be controlled precisely. Doing so results in the extraction of a large, single-crystal, cylindrical ingot from the melt. The melting process needs both, an inert atmosphere (e.g. argon) and an inert chamber (e.g. quartz). The disadvantages of the classical melting process are the very low speed and the energy intensive production costs. In addition the ingot must be sawed in order to produce thin solar cell wafer. This process is time-consuming and furthermore results in loss of valuable material. A lot of R&D effort is undertaken by the PV industry to improve the fabrication process. The appearance of the mono-Si is mostly black (see figure 2).

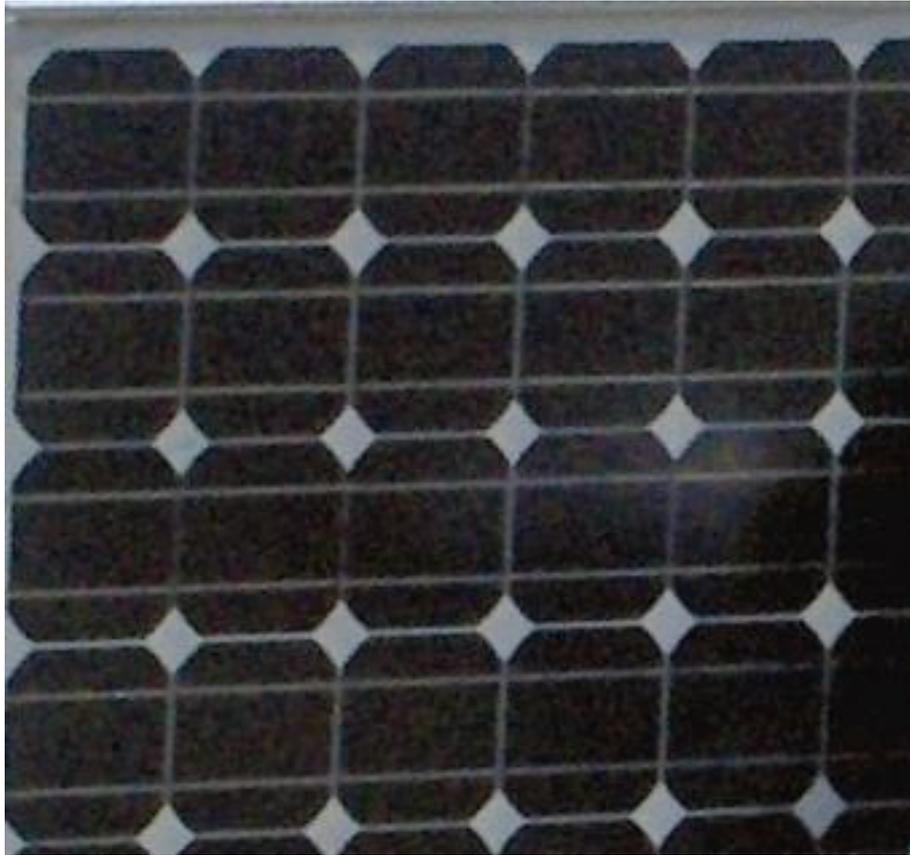


Fig 2: Monocrystalline silicon module

Multicrystalline Silicon

Multicrystalline silicon is also referred to as polycrystalline silicon or more simply poly-Si. Solar cells based on poly-Si are very similar to monocrystalline modules. The same theory applies; the main difference is the fabrication process. Poly-Si cells are fabricated from pure molten Si in a square-like tank; the cooling down is an essential step because it determines the grain size and the distribution of impurities. The obtained ingots are cut in bars with a cross-section of 15.6cm x 15.6cm; finally they are sawn to get thin wafers. This fabrication process gives life to a multi-grain crystal structure. Compared to monocrystalline Si, the structure is less ideal resulting in a loss of efficiency (of about 1% compared to mono-Si) [3], but this drawback is overcome by lower wafer costs. A second advantage is the arrangement of the cell modules which are typically rectangular, rather than “pseudo-square” compared to mono-Si, so they can be packed very closely in the modules. The appearance of the poly-Si is distinctly blue (see figure 3) due to the missing absorption of higher energy photons. In fact, these high energy photons from the upper part of the visible spectrum are back-reflected.



Fig 3: Multicrystalline silicon module

In conclusion, there is only a minor difference when comparing poly-Si versus mono-Si in terms of performance, efficiency and costs; in addition, other merits are often also very similar such as lifetime and guarantee. Finally, features such as availability and the manufacturer's reputation may play a major role as well.

From the wafer to the classical solar cell

After the fabrication of the p-type Si-Wafer, the following steps are necessary in order to get a working PV-module [4]:

- Surface treatment to clean it from defaults coming from the sawing process
- Surface etching with the aim of creating small pyramids on the surface for higher photon collection (the PV-cell is so less-orientation sensitive)
- Diffusion of phosphor to create the photovoltaic pn-junction
- Doping of the backside with a p^+ layer
- Adding a anti-reflection-film on the front side
- Connecting the metal contact between the n-layer and the top
- Adding an Al-electrode on the backside and the corresponding rear metal contact

The figure 4 shows a cross-section view of a mono-Si solar cell.

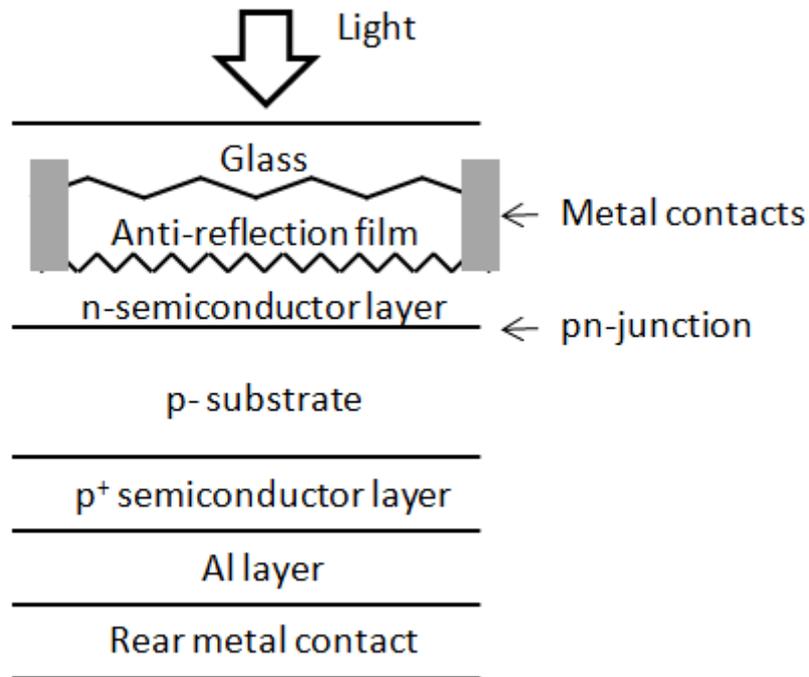


Fig. 4: Schematic cross-section view of a mono-Si solar cell

Amorphous and thin film materials

Thin film solar cells are also often called second-generation solar cells [5]. In this category fall amorphous Si-cells, CdTe cells and CIGS cells. CIGS stand for: Copper Indium Gallium Selenide. The huge advantage of these cells lies in the fact that only very little material is needed for their fabrication. The production processes are compatible with large surfaces that can be used with either flexible or rigid substrates; these properties result in a cost-effective solution for PV-cell production. In fact, thin film materials are able to efficiently absorb photons (with a up to 100 times higher absorption coefficient compared to mono- or poly-Si cells). Consequently, they need only a few micron thickness compared to about 200 μ m thickness required for the mono- or poly-Si to absorb all the photons having energy higher than the gap.

CdTe thin film cells

The CdTe thin film cells have gone through a rapid development in recent years, due to their competitiveness in terms of cost, high conversion efficiency, and the available manufacturing processes. For the time being, CdTe thin film cells are leading the thin film PV-industry. Commercial modules reach conversion efficiency of up to 12.6% [5]. CdTe has a direct band gap of 1.45eV and responds well to the solar emission spectrum.

Low cost techniques have been developed in order to fabricate these modules. Here the main fabrication steps are summarized (see also figure 5): A glass surface is covered with a SnO₂ film doped by F; the role of the SnO₂ film is double: on the downside of the film it permits to optimize the contact with the glass without absorbing too much photons and on

the upside of the film, it permits to collect the electrons (it acts as an electrode). This follows a buffer layer of CdS (100nm). Next the active CdTe layer is added (3 to 7 μ m thick) acting as a photon absorber. On the backside, a contact electrode is added in order to collect the created holes. The figure 5 below shows a schematic cross section of the CdTe thin film cell.

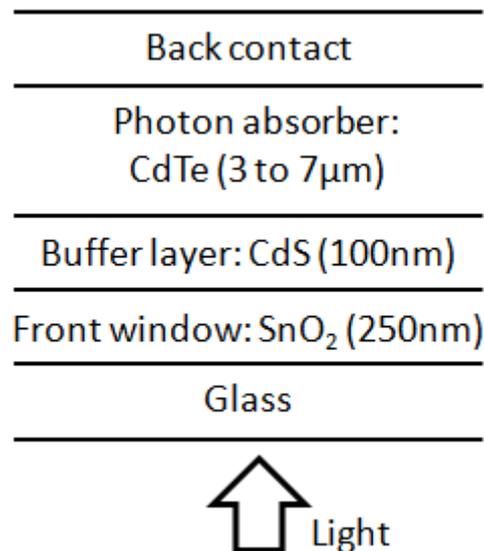


Fig. 5: Schematic cross-section view of a CdTe thin film cell

The high conversion efficiency combined with the robust structure and high production throughput accelerated the development of CdTe thin film cells. However, the use of a toxic material (Cd) requires some special attention during the production of the cells as well as during the recycling phase at the end of their lifetime. In order to discard this toxic material, other thin film materials are investigated: These are CIGS thin film cells and amorphous Si-cells.

CIGS thin film cells

CIGS solar cells fall in the category of the thin film cells. Compared to other thin film cells, CIGS solar cells are considered as the most promising one. In fact, their conversion efficiency is coming close to the conversion efficiency of poly-Si cells.

The figure 6 shows the cross-section view of a CIGS cell. Starting from the backside, a molybdenum layer is stacked on a glass substrate. The next layer consists of the photon absorber which is an alloy of Cu (In,Ga)Se₂ (di-selenide of copper, indium and gallium). The thickness of this layer is about 2 μ m and it is produced by co-evaporation under ultra-high vacuum at a substrate temperature of roughly 550°C. The substitution of In by Ga permits the adjustment of the energy gap (in between 1eV to 1.7eV). Then, a n-type buffer layer of CdS or ZnS with a thickness of about 50nm is added. It helps to optimize the interface between the CIGS-absorber, the non-doped i-ZnO layer, and the n-type top contact layer (ZnO:Al). The top layers are transparent in order to let all the photons pass to the absorber layer.

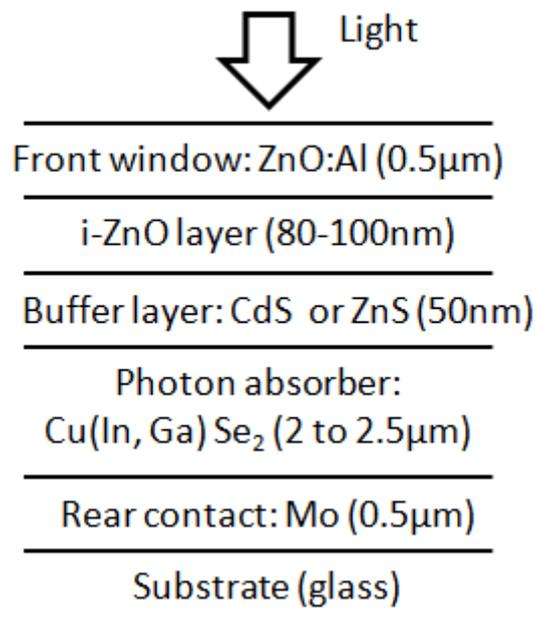


Fig. 6: Schematic cross-section view of a CIGS thin film cell

Amorphous Si-cells

Amorphous silicon (a-Si) is the non-crystalline form of silicon. Amorphous silicon panels are fabricated using the vapour-deposition process to create a thin layer of silicon material of about 1 µm thickness on a substrate material such as glass or metal. The main advantage here is the possibility to deposit amorphous silicon at very low temperatures. The basic form consists in a single sequence of p-i-n layers (see figure 7). The p-i-n layers are used in order to create an electric field that helps moving the carriers; in fact amorphous silicon has a very low mobility of about 1 cm²/Vs [6] compared to the mobility of more than 1000cm²/Vs in monocrystalline Si-cells. A well-known drawback of amorphous thin Si films is the significant degradation in their power output when exposed to the sun (in the range 15-35%). The stability can be improved when using thinner layers. However, doing so, light absorption will be reduced as well as cell conversion efficiency. A workaround consists in the use of tandem and even triple layer devices that contain p-i-n cells stacked one on top of the other. They are separated by thin tunnel junctions (not shown on the schematic cross section, figure 7). Each p-i-n cell layer has specific additional atoms in order to adjust the energy gap.

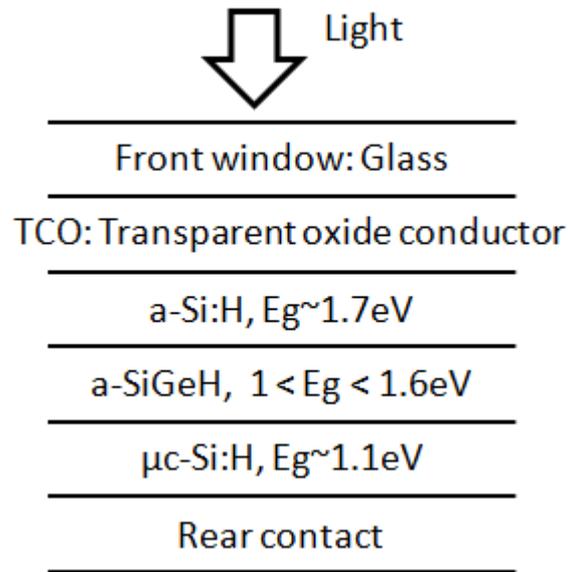


Fig. 7: Schematic cross-section view of a amorphous Si thin film cell

Discussion

So far we presented the mainstream PV technologies, which concern solid crystallized, amorphous and thin film materials. In this section, we will discuss these technologies in terms of global production and finally give a state-of-the-art of the principal figure of merit: the conversion efficiency with respect to the different technologies.

Production

In 2013, the global annual PV production was about 38.7GWp. Nine percent of the fabricated PV-modules were thin film modules, 36 % were monocrystalline Si modules and the largest part (55%), was composed of poly- (or multi-) crystalline Si PV modules. The figure 8 highlights this distribution.

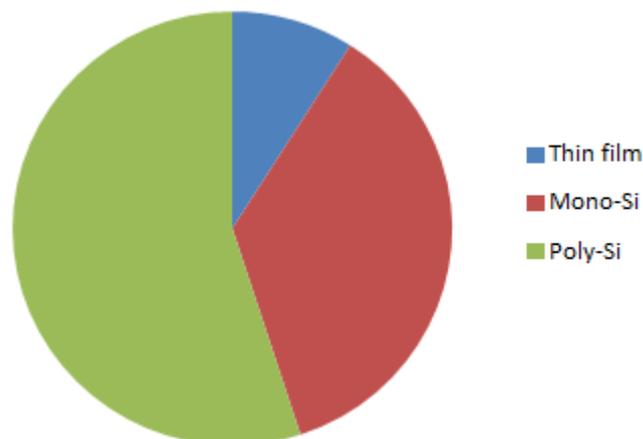


Fig. 8: PV production development by technology in 2013, data from [7]

Solar cells and modules conversion efficiency

At the end of 2014 the state-of-the-art conversion efficiency of solar cells is summarized below [7]:

- The record lab cell conversion efficiency is
 - 25 % for mono-crystalline Si cells,
 - 20.4 % for multi-crystalline Si cells,
 - 19.8 % for CIGS thin film solar cells,
 - 19.6 % for CdTe thin film solar cells.
- Conversion efficiency increases over the last 10 years of an average commercial wafer:
 - 12 % to 16 % for silicon based modules,
 - 9 % to 13 % for CdTe based modules.

Outlook: Emerging PV technologies

A huge research effort is undertaken in order to work on new materials and novel concepts for photovoltaic modules. Here we only mention the Grätzel photoelectrochemical solar cells or dye-sensitized solar cells (DSSC) [8] and the organic solar cells.

DSSCs are based on a semiconductor formed between a photo-sensitized anode and an electrolyte. The advantages of Grätzel photoelectrochemical solar cells can be summarized as follows: (i) the manufacturability cost is low, (ii) roll-to-roll processing is possible permitting high volume production, (iii) the energy payback is less than one year due to the low embodied energy in the manufacturing process; (iv) they are non-toxic, earth-abundant materials (except Pt, Ru), (v) perform well in diverse light conditions such as high angle of incidence, low intensity and partial shadowing; (vi) finally, they are (or can be) lightweight, flexible and semi-transparent. Their main challenges are the improvement in conversion efficiency, especially stability and robustness.

An organic solar cell is composed of polymers. The intrinsic organic solar cell consists in two layers: one electron donor and one electron acceptor layer. When a photon is absorbed, it creates a bound electron-hole pair (also called exciton), mostly in the donor material. It can be separated when the excitation diffuses to the donor-acceptor interface.

The material used for the production of organic solar cells is composed of polymers or in other word: plastic. The plastic used has low production costs in high volumes, which represents the main advantage of organic solar cells. In addition, the optical absorption coefficient of organic molecules is high, so a large amount of light can be absorbed with a small amount of materials. The principal disadvantages are low efficiency, low stability and low strength compared to inorganic photovoltaic cells. Research and development of organic photovoltaic technologies has delivered a device record efficiency of 12% [9] and outdoor

lifetimes beyond a year [10]. However, a few years of lifetime are still required before organic photovoltaic modules can effectively be launched into the market.

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