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Inorganic photovoltaic cells: Operating principles, technologies and efficiencies - Review

Yasser Karzazi[1,2 *], Imane Arbouch[1]
[1] *Laboratory of Applied Chemistry and Environment (URAC 18), Faculty of Sciences, University of Mohammed Premier, B.P. 4808, 60046 Oujda, Morocco*
[2] *National School of Engineering and Applied Sciences, University of Mohammed Premier, B.P. 3, 32003 Sidi Bouafif, ENSA Al Hoceima, Morocco.*

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[*] *Corresponding Author. E-mail: karzazi@hotmail.com*

Abstract

The search for new alternatives to fossil energies has pioneered the development of green energies. Since the seventies, solar energy due to its abundance has been one of the main renewable energies that received tremendous efforts in terms of research in the fields of chemistry, engineering and physics. This is driven by the fact that the energy striking the surface of the earth in one hour is enough to power the planet for an entire year. Therefore, no other renewable energy sources have such a capacity to meet all the planet's energy needs for the foreseeable future. Nowadays, the majority of commercial solar cells are based on the inorganic photovoltaic technology which utilizes a silicon wafer in either single-crystal or polycrystalline form for light absorption and a p-n junction for charge separation. In this paper, the solar energy is described and quantified, along with a review of semiconductor properties, photovoltaic conversion operations and the basic inorganic photovoltaic cells technologies. Particular attention is given to p-n junction, including losses and Shockley-Queisser limit. Crystalline silicon photovoltaic cell, thin film technologies and multijunction photovoltaic cells are described for the photovoltaic conversion. Finally, structure devices and cell efficiencies are examined and discussed.

Keywords: Inorganic photovoltaic cells, p-n junction, semi-conductor, energy conversion efficiency, crystalline silicon cells, thin film technology, multijunction.

1. Introduction

In 1839, the French physicist E. Becquerel noted that a string of semiconductor elements gave rise to a spontaneous power when enlightened. This physical phenomenon known as the photovoltaic effect was explained by Einstein in 1912. Efficient photovoltaic cells for the conversion of solar energy into electric energy were firstly demonstrated at Bell laboratory in 1954 [1]. These cells were used in space applications in 1958 to power the first satellites. The oil crisis, in the 1970s, gave rise to a new boom for terrestrial applications. Besides, the technology of photovoltaic cells experienced a slowdown in the early 1990s, before a spectacular recovery since the 2000s. This rebound is explained by announced shortage of fossil resources and environmental challenges of global warming. Noteworthy, the exploitable portion of the solar energy is three times more than the energy consumed worldwide. This energy that seems inexhaustible on a human scale is totally respectful of the environment: its use produces no waste or greenhouse gas emission. Currently, trends in photovoltaic industry show accelerated development associated with intense research aimed at increasing the efficiency of energy conversion and reducing the cost of photovoltaic cells manufacturing to make this source of energy more competitive. Two photovoltaic technologies are in competition nowadays, in this work, we focus on inorganic photovoltaic cells which accounts more than 90% of the market with respect to that of organic photovoltaic cells [2,3]. On the one hand, this review article outlines the concept of inorganic photovoltaic cells, detailing the operation principles and performance characteristics. On the other hand, device structures of the mainstream inorganic photovoltaic cells are described along with a comparison of their conversion efficiencies.

2. Operation principles

2.1. Solar irradiance

The Sun is a nuclear fusion reactor emitting a powerful amount of energy in the space (63 500 kW/m^2) by a transformation process of hydrogen into helium. Solar energy arrives in the form of light radiation with wavelengths ranging from ultraviolet to infrared with a peak in the field of the visible located at 550 nm that is in yellow-green. The Sun radiates most of its energy in the short wavelengths. Visible light represents 46% of the total energy emitted by the sun while 49% of the radiation energy emitted by the Sun is located in the infrared. At least 35% of the solar radiation intercepted by the Earth and its atmosphere are reflected back to space. A portion of the radiation that reaches the Earth was broadcast in all directions during the crossing of the atmosphere, with air molecules, aerosols and dust particles (it is this diffuse radiation, belonging particularly to the blue fringe of the visible spectrum which is responsible for the blue colour of the clear sky). Besides, water vapour, carbon dioxide and ozone in the atmosphere absorb 10 to 15% of the solar radiation while the rest of the radiation reaches directly the surface. It must be stressed that the atmosphere absorbs and scatter more particles of light that it is thicker and denser.

Solar irradiation arrives outside the Earth's atmosphere with a power of about 1367 watts per square meter. The thickness of atmosphere traversed by the solar light spectrum has a great influence on the received power. International standards define different types of spectrum: AM1 (in Ecuador for air mass 1, when radiation passed through a thickness of atmosphere), AM0 (spectrum on the outer surface of the atmosphere), AM1.5 (spectrum used for standardized testing of solar panels corresponding to the passage of an atmosphere and a half). The maximum solar power on the surface of the Earth is about 1 000 W/m² for a surface perpendicular to the rays; it is called power 1.5, which is the reference in efficiency calculations.

2.2. Photovoltaic conversion

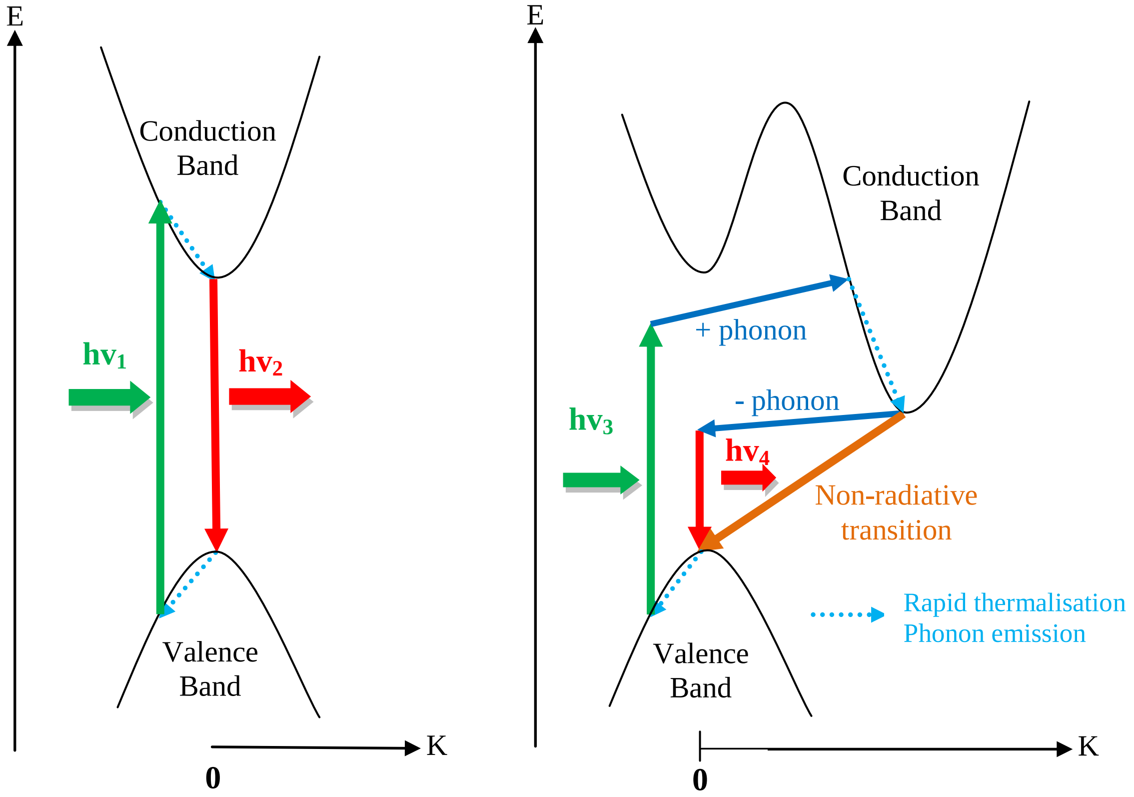
Photovoltaic energy is the conversion of solar energy into electrical energy using photovoltaic cells assembled in modules gathered in production unit. The photovoltaic conversion through inorganic photovoltaic cells requires two basic attributes:

2.2.1. Absorption of photons and generation of electron-hole pairs

To convert photons into electricity, photovoltaic cells are made of semiconductors. These materials are characterized by a band of forbidden energy named band gap that represents the difference between the valence band and the conduction band and whose width depends on the chemical nature and the structure of materials. This band gap worth 1.1 eV for crystalline silicon, 1.7 to 1.9 eV for hydrogenated amorphous silicon and 1.5 eV for gallium arsenide (GaAs). **Figure 1** plots the kinetic energy versus wave or momentum vector of the electron ($\boldsymbol{E} = \frac{\boldsymbol{k^2h^2}}{\boldsymbol{8\pi^2m^*}}$), where h is the Planck constant and $\boldsymbol{m}^*$ is the electron effective mass. The direct and indirect gap materials are distinguished by their relative positions of the conduction band minimum and the valence band maximum in the Brillouin zone (the volume of k space containing all the values of k up to π/a where a is the unit lattice cell dimension). In a direct gap material, the extrema of the conduction band and the valence band occur at the zone where k = 0. Thus, transitions inter bands occur vertically and so are radiative. This illustrates the binary III-V semiconductors such as gallium arsenide (GaAs). In the case of crystalline silicon, the gap is indirect, transitions between the extrema (which do not occur at the same value of crystal momentum in wave vector space) are oblique, and are therefore non-radiative. For the transitions occur in the indirect gap, a phonon should assist to absorb the photon. Note that the value of the indirect gap of crystalline silicon is 1.1 eV at 300 K, but that of the first direct gap worth 3.4 eV. Thus, photon absorption is more or less important depending on the semiconductor material.

2.2.2. Separation of charge carriers of opposite types

At equilibrium, the semiconductor material electrons are in the valence band and are tightly bound in covalent bonds between neighboring atoms. When a photon is absorbed, it transfers its energy to an electron which is excited from the valence band to the conduction band and it leaves a hole (equivalent to a positive charge) in the valence band **(figure 2)**. Thus, the photons absorbed in the semiconductor generate mobile electron-hole pairs. According to the principle of detailed balance, the excited electron and hole can meet spontaneously and recombine; the energy provided by the photon is thus dissipated. In fact, when an electron and hole are spatially close, a fraction of them recombine to form an exciton (a bound state of the electron and hole); which is a localized electron-hole pair having an excited energy state. Then some of these excitons relaxes via a photoemissive mechanism and decay radiatively to the ground state by spontaneous emission. This mechanism is used to produce light in diodes as organic light emitting diodes (OLEDs) [4]. Conversely, the principle of a photovoltaic cell is to use an electric field to separate the electrons from the holes before the recombination process. This electric field is commonly established across the photovoltaic cell by a p-n junction. Actually, after joining p-type and n-type semiconductors, electrons from the n region near the p–n interface tend to diffuse into the p region. As electrons diffuse, they leave positive charge in the n region. Likewise, holes from the p region near the p–n interface begin to diffuse into the n region, leaving negative charge. The regions nearby the p–n interface lose their neutrality and become charged, forming the space charge region and creating an electric field from n to p that allows electrons to move only in a single direction. Hence, electrons diffuse from p to n (but not in reverse); conversely the holes do diffuse from n to p **(figure 2).** The result is an electric current that can flow in the external circuit through ohmic metal semiconductor contacts made to both the n-type and p-type sides of the photovoltaic cell.



Direct bandgap indirect bandgap

Figure 1: Inter-band transitions of electrons in a semiconductor.

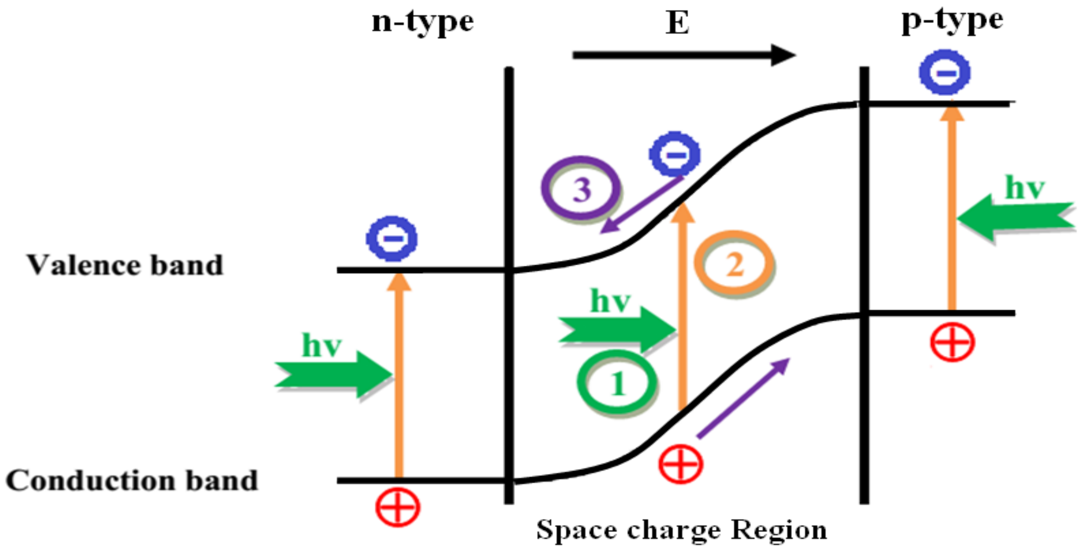


Figure 2 : Scheme of p-n junction photovoltaic cell mechanism.
(1) Absorption of photons by electrons, (2) Generation of electron-hole pair (Blue-Red).
(3) Separation of charge carriers driven by the electric field.

3. Efficiency and performance characteristics

3.1. *Energy conversion efficiency*

Photovoltaic cell efficiency is a fundamental characteristic of the photovoltaic cells. It expresses the ratio of the electrical output of a photovoltaic cell to the incident energy in the form of sunlight. The energy conversion efficiency (η) is calculated by dividing a cell's power output (in watts) at its maximum power point (P_m) by the input light (E, in W/m^2) and the surface area of the photovoltaic cell (A_c in m^2).

$$\eta = \frac{P_m}{P_{incident}} = \frac{P_m}{E \times A_c} \qquad (1)$$

Photovoltaic cell efficiencies are measured under standard test conditions (STC) which specify a temperature of 25 °C and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrum. A photovoltaic cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a short circuit) to a very high value (an open circuit) one can determine the maximum power point (P_m), the point that maximizes V×I; that is, the load for which the cell can deliver maximum electrical power at that level of irradiation.

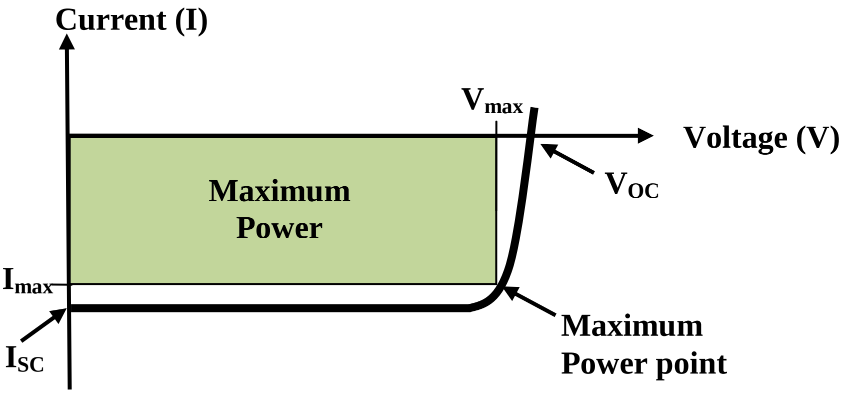


Figure 3: I-V characteristic of p-n junction photovoltaic cell.

In the ideal case, I-V characteristic is rectangular; the maximum power produced by the cell under illumination is equal to the product I_{sc} (short circuit current) ×V_{oc} (open circuit voltage). In practice, the I-V characteristic has an exponential form (Boltzmann equation), which limits the maximum power to the product I_{max} ×V_{max} **(figure 3).** Another defining term in the overall behavior of a photovoltaic cell is the fill factor (FF) which expresses the available power at the maximum power point (P_m) divided by the ideal maximum power ($V_{oc} \times I_{sc}$) :

$$FF = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \qquad (2)$$

Hence, the energy conversion efficiency (η) can be expressed by the equation **(3)** corresponding to the current-voltage characteristic of the solar cell:

$$\eta = \frac{P_{max}}{P_{incident}} = \frac{V_{max} \times I_{max}}{E \times A_c} = \frac{FF \times V_{oc} \times I_{sc}}{E \times A_c} \qquad (3)$$

3.2. Shockley–Queisser limit

Several factors affect the energy conversion efficiency value. In 1961, William Shockley and Hans Queisser have calculated the Shockley–Queisser limit which refers to the maximum theoretical efficiency of an inorganic photovoltaic cell using a p-n junction. This limit is one of the most fundamental to solar energy production, and is considered to be one of the most important contributions in the field. The Shockley–Queisser limit is calculated by examining the amount of electrical energy that is extracted per photon of incoming sunlight [5]. There are three primary considerations to calculate the maximum theoretical efficiency.

3.2.1. Blackbody radiation

Any material that is not at absolute zero (0 Kelvin) emits electromagnetic radiation through blackbody radiation. In the case of a solar cell at ambient room temperature, at 300 Kelvin, baseline energy is always being emitted.

This energy cannot be captured by the cell, and represents about 7% of the available incoming energy. This radiation effect is dependent on cell temperature. Any energy lost in a cell is generally turned into heat, so any inefficiency in the cell increases the cell temperature when it is placed in sunlight. As the temperature of the cells increases, the blackbody radiation also increases, until equilibrium is reached. In practice this equilibrium is normally reached at temperatures as high as 360 Kelvin and cells normally operate at lower efficiencies than their room temperature rating.

3.2.2. Spectrum losses

In conventional single p-n junction solar cells, a vast part of solar irradiance is not converted. In fact, the sub-band gap photons cannot generate electron-hole pairs and are therefore lost. Moreover, the above-band gap photons can generate a single electron-hole pair; the excess energy is lost due to thermalization of photocarrier. Survey of the spectrum effectively exploited by a crystalline silicon (c-Si) single p-n junction solar cell compared with the AM1.5 solar spectrum shows that thermalization loss is estimated at 33%, moreover 15% represent extraction losses while 19% of incident energy is not absorbed and thus only 33% are available [6].

3.2.3 Radiative recombination

Absorption of a photon creates an electron-hole pair, which could potentially contribute to the current. However, the reverse process must also be possible, according to the principle of detailed balance: an electron and a hole can meet and recombine, emitting a photon. This process reduces the efficiency of the cell.

3.2.4 Maximum theoretical efficiency.

Considering the spectrum losses alone, a solar cell has a peak theoretical efficiency of 48% [5]. Thus the spectrum losses represent the vast majority of lost power. Including the effects of blackbody radiation and recombination, a single-junction cell will have a theoretical peak efficiency of about 33.7% or about 337 W/m² in AM1.5 [5]. However, Shockley and Queisser's work considered the most basic physics only; there are a number of other factors that further reduce the theoretical power.

More realistic limits, which are lower than the Shockley-Queisser limit, can be then calculated by taking into account non radiative recombination (Auger). A maximum theoretical efficiency of c-Si solar cells was calculated to be 29.4% [7]. Moreover, The Shockley–Queisser limit only applies to cells with a single p-n junction; cells with multiple layers can outperform this limit. In the extreme, with an infinite number of layers, the corresponding limit is 86% using concentrated sunlight [8]. Equally important, a number of technical approaches are recently presented to overcome the Shockley–Queisser limit for a single junction by suppressing recombination processes and improving the minority carrier lifetime [9].

4. Inorganic photovoltaic cells technologies

The realization of high-efficiency photovoltaic cells with low process cost is currently the most important challenge for photovoltaic cell manufacturers. Thus, various inorganic photovoltaic cells technologies have emerged in order to optimize the ratio cost per efficiency and make this source of energy more competitive.

4.1. Crystalline silicon solar cells (c-Si)

Despite the indirect band gap lowering photon absorption, the crystalline silicon is the most prevalent bulk material for photovoltaic cells. This semiconductor has different advantages: it is one of the most abundant resources on Earth, it is not toxic and it can be doped easily with (phosphorus and boron) for the creation of p-n junction. Crystalline silicon photovoltaic cells are the most popular photovoltaic cells on the market and also provide the highest energy conversion efficiencies. Standard crystalline silicon cells are produced using one of two different boron-doped (p-type) silicon substrate; monocrystalline and polycrystalline. Monocrystalline photovoltaic cells (**figure 4a**) which are produced from pseudo-square silicon wafer substrates cut from column ingots grown by the Czochralski (CZ) process tend to be expensive and led to the highest research cells efficiency (25%) [10]. Otherwise, polycrystalline photovoltaic cells (**figure 4b**) are made from square silicon substrates cut from polycrystalline ingots grown in quartz crucibles and are less expensive to produce than monocrystalline silicon cells, but are less efficient (20.4%) [11].

The structure of conventional monocrystalline-silicon photovoltaic cell is composed by the following components:

a. Textured surface formed by micrometer-sized pyramid structures covering the front surface of the crystalline silicon cell in order to reduce reflection loss of incident light [12,13].

b. Anti-reflection coating (ARC) of titanium oxide (TiOx) or hedrogenated silicon nitride (SiNx: H) is overlayed on the textured silicon surface to further reduce reflection loss [14,15].
c. Highly phosphorous-doped n^+ regions on the front surface of boron-doped p-type substrates to form p–n junction.
d. Back-surface p^+ field (BSF) formed on the back surface of the silicon substrate to suppress recombination of minority carriers (photogenerated electrons) [16,17].
e. Front and back contacts where the electrons and holes carriers are collected by silver contacts electrodes.

Despite the dominance of conventional crystalline silicon cells in the photovoltaic market, they have significant performance limitations that limit their efficiencies to well below those achievable in research laboratories around the world [18-20]. In order to overcome these limitations and achieve higher efficiencies, many promising technologies allowing high surface and bulk passivation without resistive and optical losses have been developed. Therefore, Different structures have successively appeared: PESC (Passivated Emitter Solar Cell) [21], PERC (Passivated Emitter and Rear (local) Contact) cell [22], PERT (Passivated Emitter Rear Totally Diffused) cell and PERL (Passivated Emitter Rear Locally Diffused) cell which has led to the highest energy conversion efficiency of 25% [10,23]. Simultaneously, Other Promissing high efficiency crystalline silicon photovoltaic cells have proven their potential. We note particularly: Interdigitated Back Contact (IBC) cell [24] with conversion efficiency of 23.4% [25], heterojunction with intrinsic thin layer (HIT) solar cell that reached a conversion efficiency of 24.7% [26] and (Si-HJ IBC) which is the application of the interdigitated back contact cell in the field of amorphous/crystalline silicon heterojunction (a-Si:H/c-Si) cell with a theoretical efficiency up of 25% [27]. Nevertheless, despite the high efficiencies of these structures, they have complex cell structures that require a much longer production process and more specialized equipment compared with the conventional crystalline silicon photovoltaic cells. As a result, it is difficult for these high efficiency cells to compete commercially in terms of production cost per efficiency. Hence, the recent researches tend to develop alternative technologies requiring little or no Silicon.

4.2. Thin films

Thin film technologies have particularly enjoyed large investment due to the largely unfulfilled promise of lower cost and flexibility compared to the crystalline silicon cells and their conversion efficiencies that exceed the 20% [28]. Thin film photovoltaic cells are made by depositing one or more thin layers of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers (**figure 4c**). Many photovoltaic materials are deposited with various deposition methods on a variety of substrates. Amorphous silicon (a-Si), Cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and copper zinc tin sulfide (CZTS) are the four main thin-film technologies.

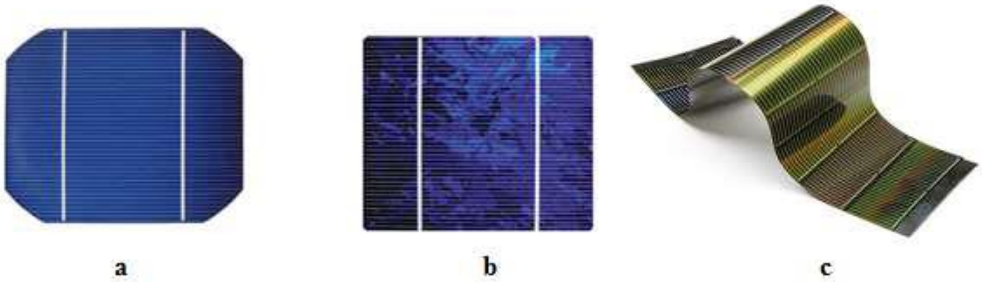


Figure 4: a: Monocrystalline silicon solar cell; **b**: Multicrystalline silicon solar cell; **c**: Thin film cell.

4.2.1. Amorphous silicon (a-Si)

Amorphous silicon (a-Si) cells have emerged in 1976 [29] and have marked an important transition between crystalline silicon photovoltaic cells and thin films. Amorphous silicon (a-Si) is a popular photovoltaic cell material owing to its low cost and ease of production. Due to its disordered structure, the generated charge carriers have more difficulties to move leading to relatively low solar cell efficiency [30]. Amorphous silicon (a-Si) thin film photovoltaic cells are usually based on p-i-n junction. Three amorphous silicon layers: p-layer (doped p), i-layer (intrinsic layer non doped) and n-layer (doped n) are formed consecutively onto a glass commonly used as superstrate and deposited by plasma-enhanced chemical vapor deposition (PECVD) from silane gas and hydrogen gas. The front contact is ensured by a transparent conducting oxide (TCO) while a reflective conducting layer (often aluminum) is used as back contact (**figure 5**).

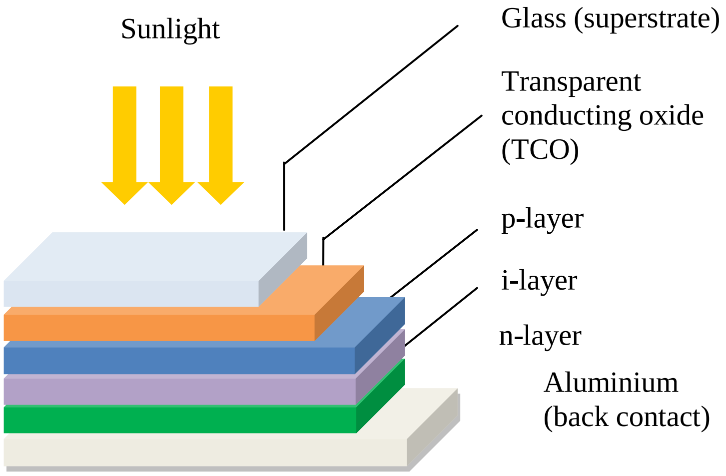


Figure 5: Schematic of amorphous silicon (a-Si) cell structure.

Low efficiencies of a-Si cells are offset by low manufacturing costs and the ease to obtain large areas. In terms of performance a major advance has been occurred with the discovery of other structural forms intermediate between amorphous silicon and crystalline silicon such as polymorphous silicon [31] and microcrystalline silicon (nc-Si) [32]. Actually, nc-Si and a-Si can advantageously be combined in thin layers, creating a layered cell called a tandem cell. The use of protocrystalline silicon for the intrinsic layer has shown to optimize the performance of an amorphous silicon photovoltaic cell [33]. Another technical approach to enhance the amorphous silicon photovoltaic cell performance is stacking three p-i-n junctions rather than a single junction leading to an efficiency of 13.4% [34].

4.2.2. Cadmium telluride (CdTe)

Cadmium telluride solar cells are based on p-n junction created particularly by the contact between two different materials, this design is called heterojunction (**figure 7**). The n-layer is a transparent semiconductor with a wide band gap (cadmium sulfide: CdS) called ‘window layer’, the photons that pass through it are then absorbed by a p-layer of cadmium telluride called ‘absorber’. The cell is completed by adding top and bottom contacts, a transparent conducting oxide layer (TCO) as front contact and metals or carbon paste with copper as back contact. The most common CdTe cell structure is shown in **figure 6**, the layer are deposited onto a glass ‘superstrate’ that allows sunlight to enter. Cadmium telluride cells have a simple design, are easy to manufacture and lead to an efficiency of 19.6% [35]. Nevertheless, the major disadvantage of this thin film technology which is the only thin film material so far to rival crystalline silicon in cost/efficiency is that cadmium is a deadly poison which must be handling with big caution and a special care must be paid to its recycling. Another issue is that tellurium is a metal extremely rare in the earth's crust. Hence, CdTe cells have no chance at a primary role in solving the question of fossil fuel replacement in the long term.

4.2.3. CIGS

Copper indium gallium selenide (CIGS) is one of the mainstream thin-film technologies. CIGS cells design is composed of a n-layer of CdS as window layer, a thin p-layer of CIGS used as absorber, a molybdenum layer and a transparent conducting oxide used respectively as back and front contact (**figure 7a**). Owing to the number of CIGS elements, CIGS has the advantage of high flexibility to optimize some properties such as the band gap and electron affinity. Then, indium which is a rare element can be replaced partially by the gallium and selenium by sulfure. These options offer possibilities to increase the CIGS cells performance. In terms of manufacturing cost, new trends of CIGS research has been focused on lower-cost deposition methods involving non-vacuum-based process and electro deposition as an alternative to expensive vacuum processes. CIGS layers are thin enough to be flexible, allowing them to be deposited on flexible substrate. Actually, the world record efficiency of 20.8% is reached by a rigid CIGS cell [28]; higher efficiencies could be obtained using optics to concentrate the incident light. These improvements in efficiency and manufacturing cost have made CIGS a leader among alternative cell materials.

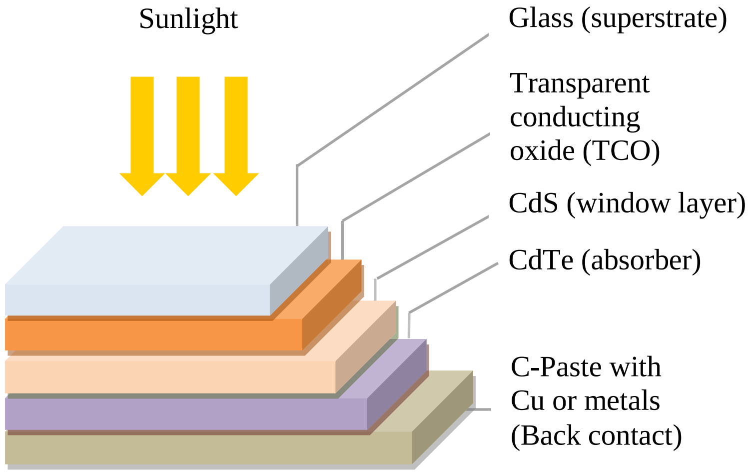


Figure 6: Schematic of Cadmium Telluride (CdTe) cell structure.

4.2.4. Copper zinc tin sulfide (CZTS)

The structure of CZTS cells is similar to the one of CIGS (**figure 7b**). CZTS is a quaternary semiconducting compound which has received a tremendous interest for applications in solar cells especially with the expected shortage of indium. CZTS offers favorable optical and electronic properties similar to CIGS making it well suited for use as a thin-film solar cell absorber layer, but unlike CIGS (or other thin films such as CdTe), CZTS is composed of only abundant and non-toxic elements. Concerns with the price and availability of indium in CIGS and tellurium in CdTe, as well as toxicity of cadmium have been a large motivator to search for alternative thin film solar cell materials. Recent material improvements for CZTS have increased efficiency to 12.6% in laboratory cells [36].

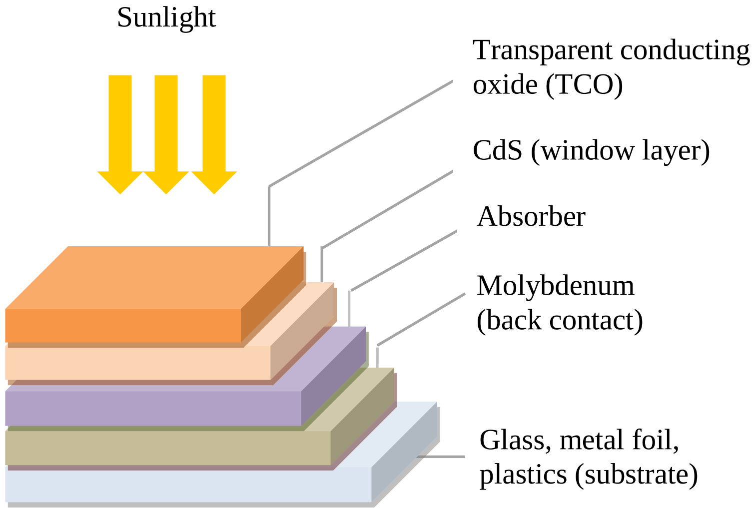


Figure 7: a: Schematic of CIGS photovoltaic cell structure (the absorber is CIGS); **b:** Schematic of CZTS photovoltaic cell structure (the absorber is CZTS).

4.3. Multijunction cells (CSP)

Multi-junction photovoltaic cells or concentrating solar power (CSP) are photovoltaic cells with multiple p-n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to a different wavelength of light. A multi-junction photovoltaic cell will produce electric current at multiple wavelengths of light, increasing the energy conversion efficiency. In a triple junction cell for example, the first junction is composed of a semiconductor with a wide band gap that converts efficiently ultraviolet photons by minimizing the thermalization losses, a second junction is equipped with a lower band gap that converts optimally visible photons, and finally the third small band gap junction which converts the infrared photons. Combinations of semiconductors are carefully chosen to efficiently absorb most of the solar spectrum, thus multi-junction solar cells absorb each color of light with a material that has a band gap equal to the photon energy. III-V multijunction devices using (III-V compounds) [37] are the most efficient solar cells to date. Multjunction photovoltaic cells were dedicated primarily to space applications because of their prohibitive cost but are also now used effectively with terrestrial solar concentrators. Several works aimed at minimizing multijunction cells cost have been developed recently. We note the inverted metamorphic multijunction, which is fundamentally a new technology path with breakthrough performance and cost advantages [38]. Multijunction photovoltaic cells efficiency using triple junction cells at high solar concentrations reaches 44.4% [35].

5. Comparative study

To further reduce the cost of inorganic photovoltaic cells, researchers have developed several technologies. Nevertheless, the crystalline silicon photovoltaic cells dominate currently the photovoltaic market. This can be explained by the abundance of silicon on the Earth's crust as well as by its physico-chemical properties translated by a good energy conversion efficiency. The crystalline silicon photovoltaic cells are produced from two different silicon substrates, monocrystalline silicon which is expensive and led to the highest research efficienccy (25%) and multicrystalline silicon which is less expensive but less efficient (20.4%). However, despite their high efficiency, the crystalline silicon cells thickness (hundreds of micrometers) that makes them especially rigid and heavy as well as their high processing cost led researchers to develop alternative technologies requiring little or no Silicon. Thin film technologies have particularly enjoyed large investment due to the largely unfulfilled promise of lower cost and flexibility compared to the crystalline silicon cells and their conversion efficiencies that exceed the 20% **(Table 1).**

Table 1: Characteristics and performance of the mainstream inorganic photovoltaic cells technologies:

Inorganic photovoltaic cells technologies	Best research efficiencies	Major Disadvantage
Monocrystalline silicon (sc-Si)	25%	Heavy-Rigid
Multicrystalline silicon (mc-Si)	20.40%	Heavy-Rigid
Amorphous silicon (a-Si)	13.40%	Efficiency
Cadmium Telluride (CdTe)	19.60%	Toxic and rare elements
Copper-Indium-Gallium-Selenide (CIGS)	20.80%	Rare elements
Copper-Zinc-Tin-Sulfide (CZTS)	12.60%	Efficiency
Multijunction cells (CSP)	44.40%	Cost

The four mainstream thin film technologies are so far to rival crystalline silicon cells in long term. Actually, the amorphous silicon cells which have a low cost manufacturing have shown a low efficiency of 13.4%; the CdTe cells which have a good conversion efficiency of 19.6% suffer from the cadmium toxicity and the tellurium unavailability. The CIGS film which is the leader among thin film technologies with a conversion efficiency of 20. 8% suffers from the expected shortage of indium, one of its principal elements and CZTS cells that have emerged especially to replace the CIGS have unfortunately a low conversion efficiency that barely reached 12.6%. Although these various breakdowns (**Table 1**), it has been conclusively proven that thin film technologies have marked a transition in the photovoltaic market last decade. Equally important, multijunction design is another efficient alternative technology that has been proposed to improve the conversion efficiency beyond that of a single junction. Unfortunately, in spite of their high potential translated by a conversion efficiency that reached 44.4%, their prohibitive cost has limited their use for concentrated photovoltaic system. Although conversion efficiency stills the most crucial metric to evaluate the photovoltaic technologies; manufacturing cost is considered as determinative factor for the photovoltaic market competitiveness. Hence, crystalline silicon is the optimum of the dilemma between high conversion efficiency and low cost manufacturing.

Conclusion

We have presented the concept and the performance characteristics of inorganic photovoltaic cells along with a description of device structures of the mainstream technologies. Best research efficiencies and technologies drawbacks are then discussed. The leader of inorganic photovoltaic technologies is the crystalline silicon cells which maintain currently the highest energy conversion efficiency. The alternative technologies such as thin films and multijunction design have highlighted an outstanding growth in terms of efficiency but have failed to compete crystalline silicon cells in terms of cost per efficiency. Hence, the recent researches tend to develop novel technologies such as Dye Sensitized Solar Cells (DSSC) [39-40], organic photovoltaic cells (OPVC) [41-42], quantum dot solar cells (QDSCs) [43-44] and photon management [45-46] as well as the development on crystalline silicon photovoltaic cells device structure continues.

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