# Materials for Solar Cells: Review and Recent Developments

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## ABSTRACT

A solar cell is an electronic device which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a p-n junction. With regard to the development of sustainable energy, such as solar energy photovoltaic cell technology has grown extraordinarily source of energy, as a consequence of the increasing concern over the impact of fossil fuel-based energy on global warming and climate change. The main goal of this review is to show the current state of art on photovoltaic cell technology in terms of the materials used for the manufacture, efficiency and production costs. Finally, conclusions and future perspectives are summarized.

## Keywords

Photovoltaics, generations, polymers, carbon nanotubes, graphene, efficiency.

## INTRODUCTION

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels. Solar cells are described as being photovoltaic irrespective of whether the source is sunlight or an artificial light. They are used as a photo detector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity. Solar cells are typically named after the semiconducting material they are made of. These materials must have certain characteristics in order to absorb sunlight. Some cells are designed to handle sunlight that reaches the Earth's surface, while others are optimized for use in space. Solar cells can be made of only one single layer of light-absorbing material (single-junction) or use multiple physical configurations (multi-junctions) to take advantage of various absorption and charge separation mechanisms.

The different photovoltaic cells developed up to date can be classified into four main categories called generations and the current market is mainly covered by the first two generations. The first generation (mono or polycrystalline silicon cells and gallium arsenide) comprises well-known medium/low cost technologies that lead to moderate yields. The **second generation** (thin-film technologies) includes devices that have lower efficiency albeit are cheaper to manufacture. The **third generation** presents the use of novel materials, as well as a great variability of designs, and comprises expensive but very efficient cells. The **fourth generation**, also known as "inorganics-in-organics", combines the low cost/flexibility of polymer thin films with the stability of novel inorganic nanostructures (i.e., metal nanoparticles and metal oxides) with organic-based nanomaterials (i.e., carbon nanotubes, graphene and its derivatives).

## TYPES OF SOLAR CELLS

1) **Mono-Crystalline Cells**

Mono-crystalline solar cells are made from single crystalline silicon. They have an incredibly distinctive appearance, as they are often coloured. The cells themselves also tend to have quite a cylindrical shape. So that they can keep the costs low and the performance at optimal levels, manufacturers tend to cut out the four sides of the mono-crystalline cells. While this gives them their recognizable appearance, it is also quite a wasteful process. They tend to have the highest levels of efficiency and are considered the highest quality of the three main types of material.

2) **Polycrystalline Solar Cells:**

Polycrystalline solar panels were first introduced to the public in 1981. Unlike their mono-crystalline counterparts, polycrystalline cells do not require each of the four sides to be cut – which results in less waste. Instead of cutting, the silicon is melted and poured into square moulds. These then result in perfectly shaped square cells. The polycrystalline solar panel is considered to be the mid-range panels in terms of price and efficiency out of the three main materials used.

3) **Thin Film Solar Cells:**

Thin film solar cells are manufactured by placing several thin layers of photovoltaic on top of each other to create the module. There are actually a few different types of thin film solar cell, and the way in which they differ from each other comes down to the material used for the PV layers. The types are as follows:

- Amorphous Silicon
- Cadmium Telluride
- Copper Indium Gallium Selenide
- Organic PV Cells

Thin film solar cells are considered to be the cheapest option when it comes to solar panels, but they are also the least efficient. However, thin film solar cells also have the most potential for the future.

## MATERIALS USED FOR THE CONSTRUCTION OF PHOTOVOLTAIC CELLS

Special materials are used for the construction of photovoltaic cells. These materials are called semiconductors. The most commonly used semiconductor material for the construction of photovoltaic cells is silicon. Several forms of silicon are used for the construction; they are single-crystalline, multi-crystalline and amorphous. Other materials used for the construction of photovoltaic cells are polycrystalline thin films such as Copper Indium Diselenide, Cadmium Telluride, and Gallium Arsenide.

1) **Silicon - The Most Popular Material for Solar Cells**

A number of the earliest photovoltaic (PV) devices have been manufactured using silicon as the solar cell material and it is still the most popular material for solar cells today. The molecular structure of single-crystal silicon is uniform. This uniformity is ideal for the transfer of electrons efficiently through the material. However, in order to make an effective photovoltaic cell, silicon needs to be "doped" with other elements.

Multi-Crystalline Silicon is normally considered less efficient than single-crystal silicon. On the other hand, multi-crystalline silicon devices are less expensive to produce. The casting process is the most common means of producing multi-crystalline silicon on a commercial scale.

Amorphous Silicon can absorb 40 times more solar radiation than single-crystal silicon. This is one of the main reasons why amorphous silicon can reduce the cost of photovoltaics. Amorphous silicon can be coated on low-cost substrates such as plastics and glass. This makes amorphous silicon ideal for building-integrated photovoltaic products.

2) **Polycrystalline Thin Films - Reducing Material Required in Solar Cells**

Numerous Thin-Film Technologies are currently being developed to decrease the amount of light absorbing material required to produce solar cells. This could lead to a reduction in the processing costs; however, it could also lead to a reduction in energy conversion efficiency.

3) **Copper Indium Diselenide**

Copper Indium Diselenide, CIS for short, has an extremely high absorptivity. This means that 99% of the light illuminated on CIS will be consumed in the first micrometer of the material. The addition of a small amount of gallium will improve the efficiency of the photovoltaic device. This is commonly referred to as Copper Indium Gallium Diselenide or CIGS Photovoltaic Cell.

4) **Cadmium Telluride**

Cadmium Telluride or CdTe is another well-known polycrystalline thin-film material. Similar to copper indium diselenide, CdTe also has a very high absorptivity and can be produced using low-cost techniques. The properties of CdTe can be altered by the addition of alloying elements such as mercury and zinc.

5) **Gallium Arsenide**

Gallium arsenide or GaAs is a compound of two elements: Gallium and Arsenic. Gallium is rarer than gold and is a byproduct of the smelting of other metals, particularly Aluminum and Zinc. Arsenic, on the other hand, is not rare, however, it is poisonous. Gallium

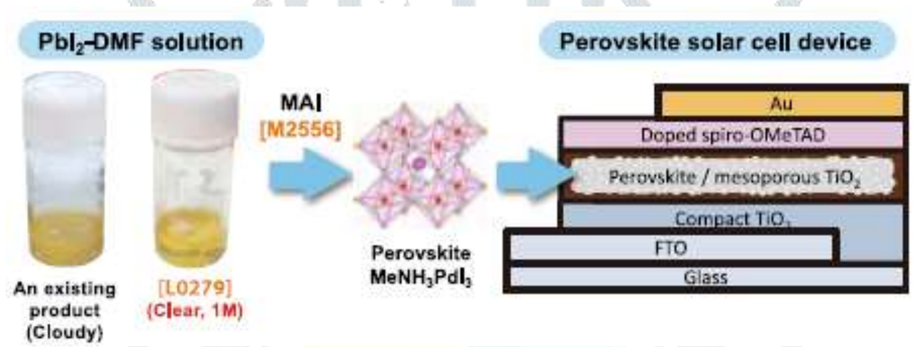
Arsenide also has a very high absorptivity and it only requires a cell of a few microns thick to absorb sunlight. GaAs cells are unaffected by heat and are highly resistant to damage from radiation. This makes it suitable for concentrator systems and space applications.

## NEWER MATERIALS

Several new solar cell materials have been developed recently. However, most of these are still in the research stages. Apart from inorganic materials, several polymer-based materials and light-absorbing dyes have been used.

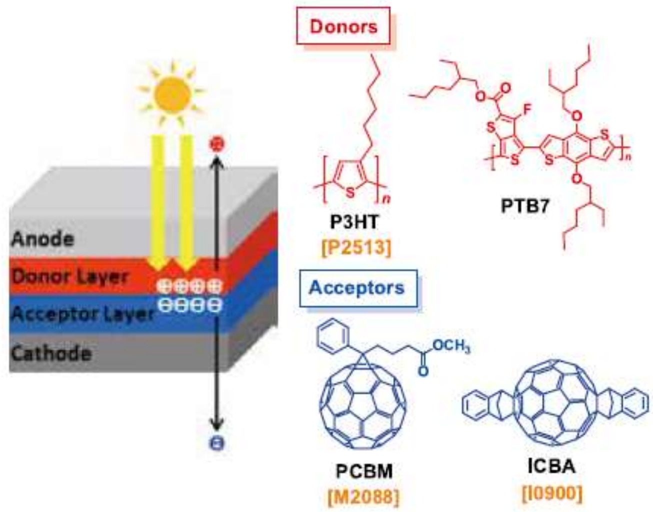
### 1) Perovskite Materials

A Perovskite Solar Cell that was first reported by Miyasaka et al. in 2009 has recently received much attention. The organic-inorganic perovskite, $RNH_3PbX_3$ (X = Cl, Br, I; R = Me, NH=CH, etc.), can function as a light absorption layer. Since 2012, power conversion efficiency (PCE) of the perovskite solar cell has been drastically improved and it has reached >15% better than those of OPV and DSSC. A device of the perovskite solar cell is solution-processible for fabrication at low cost. The organic-inorganic perovskites $RNH_3PbX_3$ are easily prepared from HX salts of organic amines and lead halides. A modification of the halide X in the $(MeNH_3)PbX_3$ can control the range of absorption wavelength. The perovskite compound with X = Br is useful for light absorption in shorter wavelengths and the compound with X = I is relatively useful for that in longer wavelengths. Wakamiya et al. reported that use of highly dried lead (II) iodide is a key to fabricate efficient perovskite solar cell devices (PCE > 10%) with high reproducibility. Carrier behavior in the perovskite layer is different from that in OPV, thus there are free carriers in which electrons and holes can be movable freely. According to the reason, the perovskite layer can transport both electron and hole carriers without recombination. One of the key advantages of these materials is their ability to absorb sunlight across the entire visible spectrum.



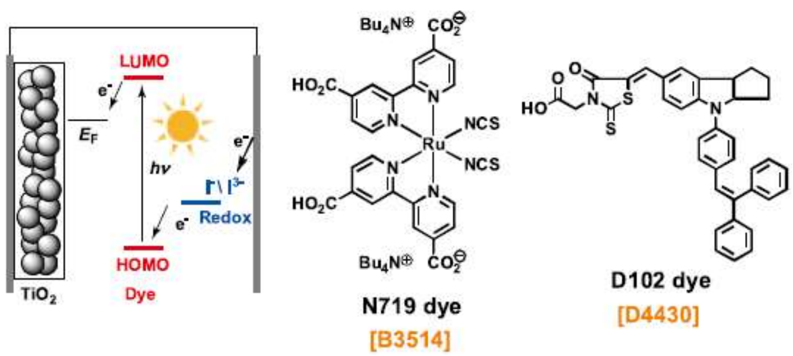

### 2) Organic Photovoltaics (OPV) Materials

A prototype of organic photovoltaics (OPV) was reported by Tang et al. in 1986. In order to fabricate an OPV device, we can use highly productive methods such as printing and roll-to-roll methods. The OPV device usually requires bulk heterojunctions (BHJ) which can be fabricated by mixing an electron-donor (p-type semiconductor) and electron-acceptor (n-type semiconductor). The former material involves a p-conjugated polymer and a small molecule semiconductor, and the latter material is normally a fullerene derivative. PCBM, that is a solubility-enhanced fullerene, efficiently provides a bulk heterojunction. ICBM gives a high open-circuit voltage because it has a higher energy LUMO than that of PCBM. A $C_{70}$ derivative usually gives higher cell efficiency compared with that of the corresponding $C_{60}$ one, because the $C_{70}$ derivative absorbs light better than the $C_{60}$. We can introduce an acceptor component into the structure of a p-type semiconducting polymer to form a donor-acceptor (DA-type) polymer that shows light absorption in the long wavelength area based on a charge transfer.




**3) Dye-Sensitized Solar Cell (DSSC) Materials**

Grätzel et al. first developed a dye-sensitized solar cell (DSSC) in 1991. The DSSC is a liquid-type device that involves nanoporous titanium oxide ($TiO_2$) as a semiconducting electrode, organic dye-sensitizer and an electrolyte solution containing a redox component. This is expected to be a low cost solar cell, because there is a simple device structure compared with other solar cells. The DSSC is usable under conditions with weak light. Thus, it is expected that the DSSC may be installed in a room. A ruthenium complex with a bipyridine ligand is one popular organic dye for solar cells. In the polypyridine ligand of the ruthenium complex, we can introduce some carboxyl or phosphonic acid groups forming a linkage with $TiO_2$. In addition, metal-free organic dyes (eg. D-102, D-131 and D-358) were also developed, because they do not contain any expensive ruthenium atoms. Recently, efficient green-colored zinc-porphyrin dyes were developed for DSSC showing more than 10% of PCE. Furthermore, efficient blue-colored metal-free organic dyes having a diketopyrrolopyrrole structure were developed for DSSC (PCE > 10%).




**4) Quantum Dots**

Nano particles, a few nm in size, called quantum dots are another type of emerging materials used in solar cells. They are low band gap semiconductor materials such as CdS, CdSe, and PbS. Their band gaps can be tuned over a wide range by changing the size of the particles. Many common materials used for fabricating quantum dots such as Cd and Pb are considered toxic, hence other alternative materials such as copper indium selenide are being developed.

## MATERIAL CHALLENGES FOR THE TWENTY-FIRST CENTURY

There are still significant challenges before photovoltaic energy can be a significant fraction of the overall energy production:

- Efficiencies are still significantly below those allowed by thermodynamics. As explained below, photovoltaic devices have a high theoretical energy conversion limit: above 33% for single junctions, and ultimately close to 90% if suitable materials can be found. Especially, relevant are materials for tandems, and for new conversion processes such as intermediate band or hot-carrier solar cells. Efficiencies are highly dependent on the quality of the materials and extremely sensitive to chemical and structural defects, even at low concentration.

- Materials availability and processability to achieve low cost. Extremely low cost could be achieved if highly scalable and low-cost processes (e.g. printing technologies) could be used to produce high-quality materials. Materials availability was also seen to enter the equation in the past decade, as the growth of the production causes concerns about the long-term sustainability of the technology.
- Durability and material aging at solar cell and module level are also an issue as this affects the reliability of the technology and also ultimately the cost. This concerns a lot structure materials and encapsulation, but intrinsic stability of the active materials was often found to be an issue to be solved first, and caused the failure of some technologies in the past, as e.g. $Cu_2S$/CdS.

## CONCLUSIONS AND FUTURE PERSPECTIVES

Currently, photovoltaic technology is regarded as a part of the solution to the growing energy challenge and as a key component of future global energy production. In this work, a brief description of the state of art on photovoltaic cells has been provided.

Mostly first generation (m-Si, p-Si and GaAs) and second generation (a-Si, μc-Si, CdTe/CdS, and CIGS) technologies are highly standardized and have undergone few changes in recent years; they exhibit high efficiencies (20–25%) and are typically expensive, though there has been a reduction in the cost of silicon-based cells. On the other hand, the majority of third generation (QDs, perovskite, PSCs, DSSCs), as well as fourth generation (polymers combined with metal nanoparticles, CNTs, G or its derivatives) technologies are in states very close to the so-called "basic research"; laboratory prototypes that lead to good results have been developed though they have not been implemented at an industrial scale yet (efficiencies 10–15%). However, the third generation multi-junction cells are already commercial, and have achieved very high energy conversion rates (>40%), thus becoming the best alternative if efficiency is sought. Fourth generation cells based on CNTs, G or its derivatives are in a state of early-research, hence constitute a very promising field for investigation. The versatile nature of such carbon nanostructures, allows to incorporate them throughout the PSC architecture, including transport layers, active layer, and electrodes, with the aim to attain inexpensive stable devices with improved performance. Both G and CNTs have been shown to be an effective, solution processable, replacement for traditional transport layers such as PEDOT:PSS. Furthermore, CNT doping has been proved to be effective for tuning the charge transport within the active layers. Additionally, there is also promise in the fabrication of hybrid architectures involving metal oxide/carbon nanostructures as transport layers in DSSCs. Despite the increasingly evident enhancements in PSC performance due to the addition of the carbon nanostructures, they have not been introduced into the market yet, since several issues have to be addressed.

(1) New approaches that enable to synthesize high-purity and high-quality CNT or G thin films with controlled morphology and electronic properties need to be developed, since the purity, quality, band-gap, and morphology of the carbon nanostructures conditions the PSC performance. In the case of TCEs, solution processable films with an optimum balance between sheet resistance and transparency are required. Further, the functionalization and ultrasonication processes used during the fabrication of PSCs lead to a remarkable drop in the electrical conductivity of the carbon nanomaterials. Thus, the electrical properties of most conjugated polymer/carbon nanotube composites do not fulfill the requirements for TCEs and counter electrodes in PVCs.

(2) The actual specific surface area of carbon-based nanomaterials is smaller than the predictions due to their strong agglomeration tendency by means of π-π stacking interactions, and the mixture with polymers makes the issue worse. Hence, novel synthetic methods to prevent aggregation are sought.

(3) Novel doping or functionalization approaches compatible with the fabrication process of PSCs have to be designed to attain higher stability, improved charge transport and tunable energy levels in carbon-based nanomaterials.

(4) New inexpensive techniques that enable the synthesis of CNTs and G at a large scale are needed. Despite some improvements have been attained in this direction, the current methods are gravely limited by their low yields, and this needs to be addressed prior to their use in commercial applications.

It is envisaged that in the next future and after comprehensive research on the field, fourth generation PSCs incorporating carbon-based nanomaterials would offer high performance levels to rival those of traditional silicon-based cells, thus providing a new outlook for the solar energy industry.

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