



## SOLAR ENERGY MATERIALS-EVOLUTION AND NICHE APPLICATIONS: A LITERATURE REVIEW

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### ABSTRACT:

Energy demand has become a global concern over the years due to the growing population that still generates electricity from non-conventional energy sources. Currently, most of the energy produced worldwide is from fossil fuels, which are non-renewable sources and release harmful by-products which are greenhouse gases. The sun is considered to be the most abundant and clean source of renewable energy. Since silicon is the most widely used element to directly convert solar energy into electrical energy, solar cells are a relevant technology to solve our planet's energy problems. Solar cell fabrication has been extensively studied over the past several decades and has improved from one generation to the next. The first solar cells were studied and grown on silicon wafers, specifically single crystals that formed silicon-based solar cells. With further development of thin films, dye-sensitized solar cells and organic solar cells have significantly increased cell efficiency. Manufacturing costs and performance have hindered further development of the cell, although consumers still trust crystalline silicon materials, which have a fair share of the market for photovoltaics. This current review work provides specific and key features along with advantages and prospects of first (mono-poly-crystalline silicon), second (amorphous silicon and thin films) and third generation (quantum dots, dye synthesized, polymers and perovskite). Materials Evolution in Photovoltaics.

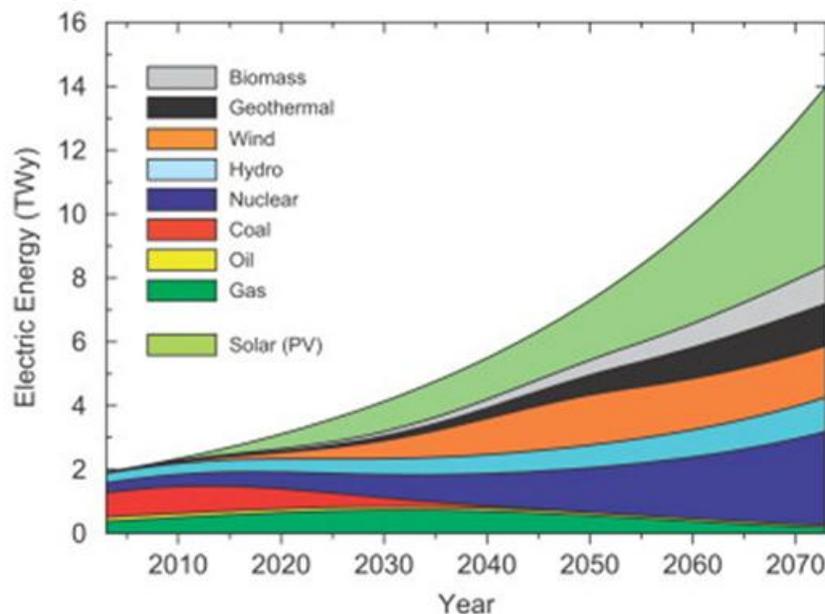
**Keywords:** solar cells; semiconductor; thin films; photovoltaic

### 1. INTRODUCTION

Their contribution to sustainability and quality of life has led to the desire to develop, produce and explore new technologies based on renewable energy resources. Solar energy has been proven to be sustainable and has attracted a lot of attention since the sun is considered the most abundant source of clean, renewable energy. This makes solar cell technology economically viable and sustainable and allows for potential reductions in greenhouse gases, thus avoiding energy and environmental related drawbacks, making it an ideal source of energy [1-4].

Figure 1 presents the forecast and potential role of various sources in the future, including the phases of environmentally friendly and renewable energy sources. The energy sources presented in Figure 1 represent water, biomass, wind, solar and geothermal energy. All these energy sources are environment friendly and sustainable. Among the aforementioned clean energy sources, solar technology promises to be the most abundant and fastest growing sustainable renewable energy source. [5].

The expectation is based solely on the fact that CO<sub>2</sub> concentrations will remain consistently and relatively below 450 ppm/year. Figure 1 significantly indicates that by 2050, solar energy is projected to play a major role among renewable sources to contribute to this [5-7].



**Figure 1.** Presents electrical energy production for the next 6 decades (with consideration that the emission of CO<sub>2</sub> will be held under 450 ppmv). Re-used with permission [5], Copyright © 2008 Elsevier.

Photovoltaics have the potential to generate electrical energy at low cost and are environmentally friendly. Thin film solar cells are favorable candidates in the field of photovoltaics because of their minimal material consumption and increased efficiency. Three of the most well-known thin film technologies that have been extensively studied and are still under intensive investigation include star absorbing materials such as  $\alpha$ -silicon ( $\alpha$ -Si), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe). Conventional inorganic silicon modules, known as first-generation solar cells, are the leading solar technology for most residential and industrial markets. Currently, crystalline silicon wafers based on high quality float zones have realized a competitive advantage over conventional solar cells through the use of a carrier-selective layer approach [8].

Amorphous silicon embedded in an internal hydrogen layer placed on one or both sides of the float zone silicon wafer acts as a passivation layer for the pre-induced carrier-selective contact. Furthermore, the above architecture reported a power conversion efficiency of 26.6% obtained from a matrix of interdigitated back contact and heterojunction technology, reaching the theoretical limit power conversion efficiency (PCE) of 29.1% for silicon solar cells. Despite interesting features and strong scalability for industrial and commercial applications, the fabrication cost of this technology has remained stagnant, making solar panels expensive [8].

Thus, these shortcomings and limitations have led to the desire to research alternative materials such as (CIGS) and (CdTe), known as second-generation thin film photovoltaics, to adequately compensate for the inability of silicon photovoltaics to provide viable production and manufacturing and fabrication. Cheap energy. Although crystalline silicon solar cells currently have a market share of more than 55%, the module efficiency of CIGS and CdTe technologies is almost competitive with that of crystalline solar cells with recorded efficiencies of 21.4% and 21.6%, respectively [8–11].

In parallel with emerging materials used in thin film technology, perovskite solar technology and organic solar cells, as well as dye-sensitized solar cells (DSSCs), are the most focused. These plastic

single-junction-based devices exhibit efficiencies of 25.5% [12], 16–18.1% [12–16] and 13% [12,17], respectively. These are third generation solar cells also known as plastic solar cells. Similarly, exfoliated tungsten telluride (WTe) flake (CiGSe) based multilayer thin films have been reported with a PCE of 10.87%. Furthermore, the structural manipulation of active materials for these cells has gained tremendous momentum due to their ease of production, flexibility, and simple fabrication methods [17,18].

Several studies have reported on these low-cost, complexation-free and easily fabricated organic solar cells, especially  $\pi$ -conjugated polymers. A comprehensive scientific contribution to the field of application-specific properties of  $\pi$ -conjugated polymers (eg, design, modeling, and fabrication) is notable in the quest to match the electrical conductivity properties exhibited by chemically doped polyacetylene. The above-mentioned optoelectronic properties have attracted the interest of the technology in various applications such as nano-electronics, sensors, Internet of Things (IoT), energy storage photodetectors, memory devices, field effect transistors (FET), nonlinear optical devices, electrochromic, light emitting diodes. (LEDs), and photovoltaics [18–23].

Conjugated polymers have interesting properties due to the side-chains in the polymeric material, which lead to significant thermal stability and solubility, and ultimately promote the fabrication of these nanostructure-based materials with simple techniques such as spin coating—hence, their cheap and easy solution processability. Their single- and double-bond characteristics and their interesting and sufficiently  $\pi$ -excessive nature have opened a window of opportunity for newly classified advanced materials in the field of photonics and electronics [23,24].

For this study, we propose the use of polycrystalline silicon semiconductor thin film raw material extracted from sugarcane bagasse ash (SCBA) for solar applications. SCBA is currently being used as a fuel source in boilers to generate electricity. Recent studies have shown that SCBA is rich in mineral content including silicon, iron and other minerals. Silicon is mainly found in the form of silicic acid and the composition of silicon is about 380 kg/ha. It is worth noting that pure silicon is further derived from silica (SiO<sub>2</sub>) and it has been reported that silica is bio-friendly and environmentally friendly [25,26].

Therefore, disposal of bagasse ash waste is a challenge of dumping before the environment. Currently, very little published information is available on the production of silicon nanoparticles from sugarcane bagasse ash for solar applications. Furthermore, quartz is currently the main source of nano silicon. This is achieved through sand mining, which has harmful effects on the environment such as land degradation, erosion, erosion and adverse effects on water supply and quality. Metallurgical-grade silicon (MG-Si) (600,000 tons/year) is produced by high-temperature carbothermal reduction of quartz, which requires an energy input of 50 kWh/kg [26,27].

Here, three generations of solar materials are presented, including important parameters affecting the overall power output of solar devices. The future prospects and challenges facing the current solar technology are also discussed in detail.

## **2. Overview of Solar Cell**

### **2.1. Solar Cell Principle of Operation**

cells are mainly described based on their architecture; Some consist mainly of metals (inorganic thin films), some of nanomaterials (QDs), some of polymers (referred to as organic), etc. Traditionally, solar cells are electronic devices that focus on converting sunlight directly into electrical energy as a result of the photoelectric effect. from metals and inorganic semiconductors [28]. Figure 2 below shows a typical p-n junction silicon solar cell. When sunlight energy shines on a cell, electricity is generated from photons (light particles). Electrons (–) are removed from the doped Si (n-type) and move to the positive (+) doped Si (p-type) material as shown in Figure 2 below.

### 2.1.1. Electronic Structure and Doping Mechanisms in Crystalline Silicon Electronic Structure

For the originality of electrical conductivity and advanced optical properties, i.e. low band-gap in inorganics, it is important to embrace the reactivity of these materials, whose electronic configuration is exhibited by doping agents compared to undoped inorganic materials. It is well known that the electronic structure of silicon is  $[\text{Ne}] 3s^2 3p^2$ , whereby the valence electrons use themselves to form four-bonds with neighboring (adjacent) atoms [29].

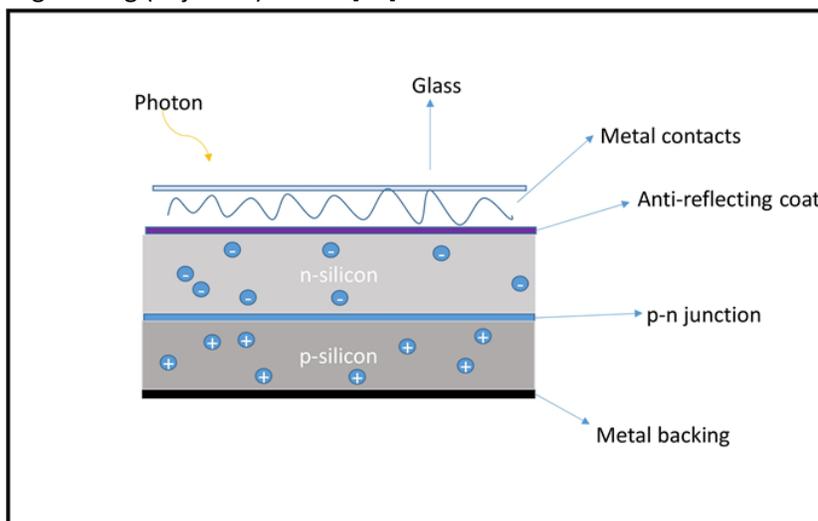


Figure 2. Schematic structure of typical a silicon solar cell [28].

#### Doping Mechanisms of Silicon Materials

Tailoring of materials to achieve electrical properties and semiconductor characteristics is done through doping. This process involves adding foreign materials and/or impurities to the material known as the extrinsic semiconductor, known as the intrinsic semiconductor, to successfully modulate its optical, electrical, and structural properties, ultimately labeled as the extrinsic semiconductor material. As a result of doping, chemical changes occur in the silicon material, resulting in the creation of charges that migrate into the silicon matrix.

There are various ways and means for doping, including redox, in situ, chemical (gas and solution), induced-radiation doping, and charge injection. In addition, these can be distinguished by the type of electron transfer, such as by doping with a reducing agent (n-type) or an oxidizing agent (p-type) [29-31].

##### 1. P-type Doping

Traditionally, silicon semiconductor doping involves the incorporation of foreign materials such as boron and phosphorus into the silicon matrix. Foreign molecules and atoms are referred to as p- and n-type dopants, respectively, due to their electronic nature. Parallel to the concept of inorganic semiconductors, charge generation occurs from the valence shell during the p-type doping process, as silicon is 1 e- more and thus creates positive charges referred to as holes, leaving the entire matrix with a positive charge. . This process uses an oxidizing agent such as boron [8,31].

##### 2. N-type Doping

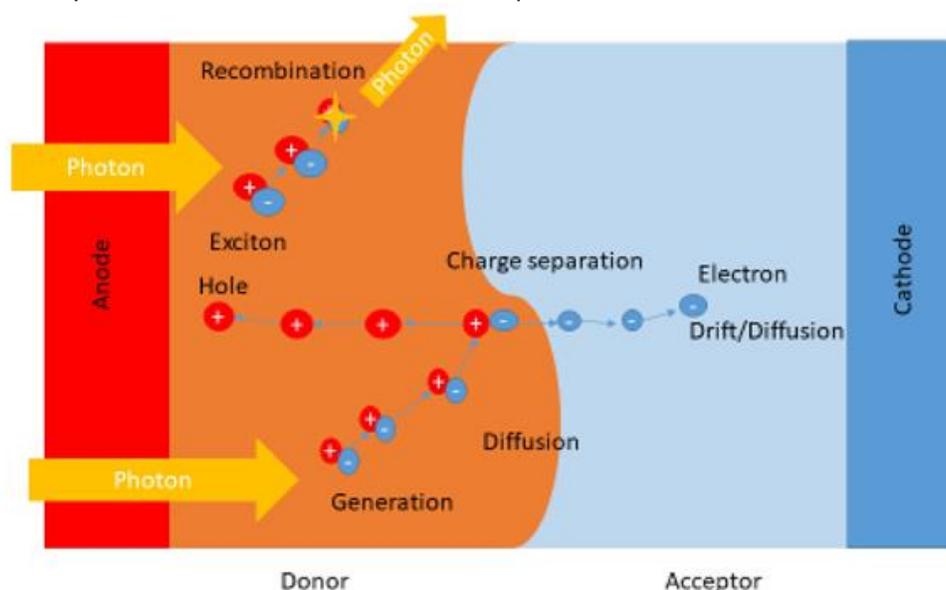
This process involves the production of electrons by a reducing agent such as phosphorus. In this case, referred to as n-type doping, the silicon matrix is modified because the reducing agent donates electrons, as shown in Figure 2, and creates a negative charge on the matrix surface. N-type doping requires materials with extra electrons compared to the parent structure, silicon, in contrast to their counterpart p-type doping [31,32].

## 2.2. Important Parameters in a Solar Device

### Principle of Charge Separation within a Solar Device

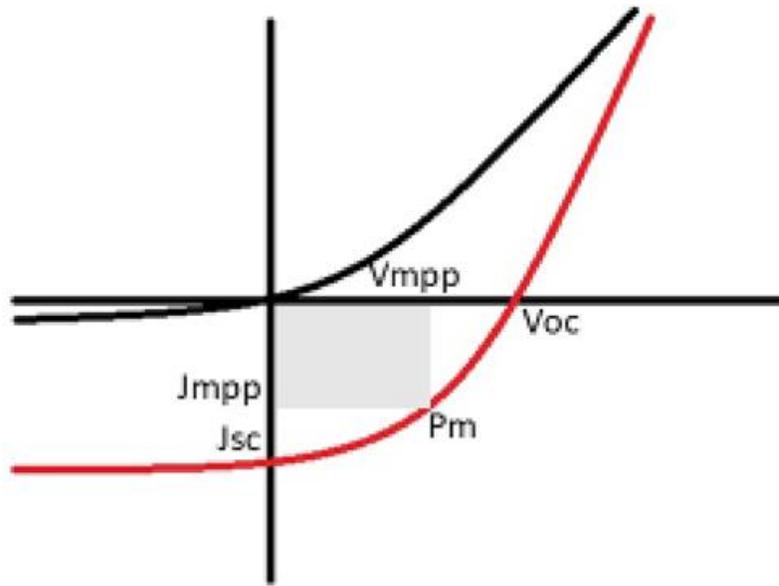
The concept of heterojunction cells depends on the efficient separation of excitons and the proximity factor of donor and acceptor materials plays an important role. The thickness of the material facilitates the optimal exciton diffusion length, typically a few tenths of a nanometer. Typically, the thickness of the active layer for organic semiconductors is in the range of 80–200 nm. Recently, large-scale heterojunctions have been deposited by co-optimization of small molecules and/or spin coating techniques using blends of polymers [33].

Drawbacks in heterojunction structures arise from the fact that hole and electron transport between the electrodes is required to promote the separation of charge carriers to reach their respective electrodes (cathode and anode). For example, if the individual layers and the given bilayer structure are larger than the exciton diffusion length, the excitons will likely recombine, as shown in Figure 3, resulting in loss of photons indicated by the exciton star. Even though the generated excitons are close to the interface, as shown in Figure 3 [33–35], they can be separated into free charge carriers and are thus likely to diffuse or be diverted to their respective electrodes.



**Figure 3.** Illustrate the principle of charge separation within a solar cell [33].

It is essential to know the solar cell performance as shown in Figure 4, which can be done by determining various factors including fill factor, efficiency, short-circuit current density and open-circuit voltage [36]. As a result of irradiation, the open-circuit voltage (VOC) is measured as the difference in cell potential across the terminals when zero current flows through the terminals. Interestingly, a short-circuit current density ( $J_{sc}$ ) is produced from the cell when it is irradiated at zero potential.



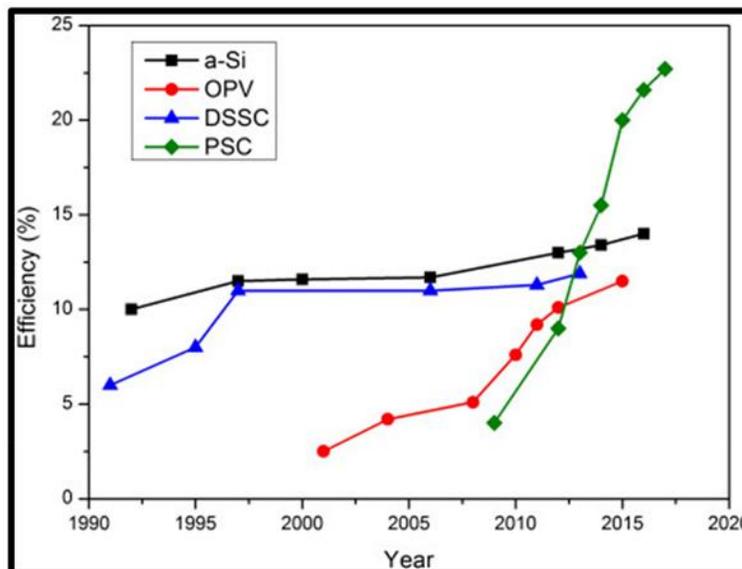
**Figure 4.** Represents a schematic current–voltage curve from a solar cell device black (dark) and red (under illumination) [36–38].

In addition, the fill factor (FF) is known as the ratio between the maximum power of the cell, shown in Equation (1) where  $V_{mpp}$  and  $J_{mpp}$  represent the voltage at the maximum power point and the current at the maximum power point, respectively.

Finally the power conversion efficiency (PCE) is determined as the ratio of the total output power of the cell to the radiant power.

Innovative designs have led to radical developments over the years, with thin film solar cell technology resulting in alternative physical device structures. The increasing efficiency of thin film solar cells, especially perovskite, which has a 23% market share, has attracted considerable attention in the photovoltaic market, mainly in the integrated photovoltaic (BIV) sector. As shown in Figure 5, plastic solar cells (perovskite) have been increasing in efficiency for over two decades, giving them potential for thin film PVs [39].

Thin film solar cells are favorable candidates in the field of photovoltaics because of their minimal material consumption and increased efficiency. The three most commonly known thin film technologies involving star absorbing materials such as  $\alpha$ -silicon ( $\alpha$ -Si), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) have been extensively studied and are still under intensive investigation. Photovoltaics have the potential to generate electrical energy at low cost and are environmentally friendly. Despite the aforementioned properties (energy conversion of a large amount of the sun's energy from these devices), these photovoltaic devices still absorb approximately 80–90% of the sun's energy and produce about 30% or less electricity [39,40].



**Figure 5.** Progress of perovskite solar cell efficiencies compared with other thin film PV technology, reused with permission from [39], Copyright © 2018 Elsevier.

### 3. The First Generation Solar Cells

#### 3.1. Crystalline Semiconductors

A crystalline material is a solid material in which the dimensional pattern of the structure is continuous and intact to the entire edge of the specimen. They are divided into different forms, eg, monocrystalline, polycrystalline, etc. Monocrystalline is a single crystal with a grain-boundary-free uniform crystal lattice, while polycrystalline materials are essential in photovoltaics with majority-carrier long diffusion lengths.

Polycrystalline semiconductors are low-cost materials compared to single-crystalline semiconductors. The first generation of solar cells were built on silicon wafers. These are the most successful technologies to date with high energy efficiency. However, limitations arise from their inhomogeneous nature and the reduced diffusion length of the carrier bulk of the material. This is a result of grain boundaries and dislocations as well as many other physical and chemical deficiencies that we encounter with these materials. A grain boundary represents a region in a material where adjacent atoms are disordered, resulting in incomplete atomic bonding. These structural defects lead to electron trapping [41].

However, many efforts have been made to reduce the amount of grain boundaries formed in polycrystalline materials. Although polycrystalline semiconductors still lag behind monocrystalline solar cells in performance, their tenable band gap makes them ideal materials and this property can be important for power conversion efficiency as well as cost (module) reduction by using less material Cost [42].

##### 3.1.1. Nanomaterials

Nanoparticles are defined as the simplest form of structures with sizes in the nanometer range. In principle, any collection of atoms with a structural radius less than 100 nm is essentially considered a nanoparticle. They differ from their bulk counterparts and isolated molecules due to their chemical, electronic and optical properties. The electronic properties of materials depend largely on their dimensions, and the density of states and the spatial length scale of electronic motion change

dramatically with decreasing size. Therefore, size-induced changes in the electronic structure affect the optical properties of nanoparticles [43].

Inorganic semiconductors have revolutionized electronic devices due to their excellent high-field-effect mobility and long-term stability greater than known organic materials. Thus they are the traditional and most professional type of electronic equipment. Their main limitations are the material selection and fabrication strategies for the use of inorganic semiconductors, as most polymer substrates are vulnerable to the high operating temperatures required for conventional deposition methods, i.e. crystallization and doping. Researchers have reported a bottom-up approach for inorganic semiconductors to fabricate zinc oxide (ZnO) nanowires. In addition, these nanomaterials have dimensions ranging from 1D to 2D with flexibility in portable electronics, as they possess excellent optical, electrical, and mechanical properties [43].

### **3.1.2. Conducting Polymers**

Conducting polymers have excellent ionic and electronic conductivity, optical transparency, and mechanical flexibility, making them excellent lightweight flexible substrates. Commonly used transparent conductive oxide elements are indium tin oxide (ITO) and fluorine-doped tin oxide (FTO). As a result of material scarcity, brittleness and cost, conducting polymers are a potential alternative for TCO due to their excellent, simple nano/microscale self-assembly, abundance and mechanical flexibility [44,45].

Commonly studied polymers include polypyrrole (PP), polythiophene (PT), polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT) and their derivatives. The above-mentioned materials have promising applications in photovoltaics, thin-film transistors, supercapacitors, gas sensors, LEDs, and wearable electronics. Moreover, their charge transport mechanism is still not well understood; It has been reported that intra chain charge transport enhancement exists as a result of new electronegative groups in the conjugated backbones and acceptor dimerization, promoting carrier mobility and stability of semiconducting polymers [44,45].

### **3.2. Single and Poly-Crystalline**

Mono-crystalline silicon solar devices are made of single crystals of silicon. Henceforth, Si materials are made with macro ingots, which result in Si crystallites (mono-crystalline Si) through a manufacturing process known as Czochralski [46–48].

Power efficiencies are in the range of 17–18% for mono-crystalline silicon-based devices reported in [48]. However, due to the expensive and complicated process of producing single crystals, researchers have opted to modify the manufacturing process. Molten silicon in a mold matrix of graphite formed a polycrystalline silicon material. Polycrystalline Si has become the most popular solar cell worldwide since 2008 due to its cost-effective properties and accounts for about 48% of solar cell production [49].

Although the densification process of molten silicon produces a variety of crystal structures and has proven to be cheaper to produce than monocrystalline silicon, it still suffers from very low efficiencies of between 12–14% [50].

## **4. Second Generation Devices (Thin Film Solar Cells)**

In search of alternative materials with better electrical and optical properties, electronics, sensors, energy etc. Nanomaterials are central to many applications in It has the ability to refine their properties at the atomic and molecular level. Attracted the attention of many researchers around the world. However, thin films have become more viable and cost-effective.

#### 4.1. Amorphous Silicon ( $\alpha$ -Si)

Second generation  $\alpha$ -Si, CIGS, and CdTe thin films take center-stage where Si is still the star material in solar technology as far as thin film solar cell evolution is concerned. The desirable characteristics of  $\alpha$ -Si, such as its direct band gap, promote the absorption of a suitable fraction of sunlight in a thin layer of a few micrometers [51].

Amorphous Si is a material with a low degree of crystallinity, suffering from loose bonds of low order leading to unphased electrical behavior with transiently small carrier diffusion lengths. Further studies were conducted which attempted to improve upon the above; Hydrogen passivation ( $\alpha$ -Si:H) has been proven to be a process to reduce the density of loose bonds, which improves the minority carrier length properties [51].

Functionalization with H<sub>2</sub> led to a degradation of light known as Staebler-Wronsky, thereby reducing the maximum power generation efficiency. The optical band gap of  $\alpha$ -Si:H of  $\approx 1.7$  eV can exceed 2 eV where the absorption maximum begins. Furthermore, it offers advantages such as low payback time (energy) and cost-effective fabrication [8,51].

#### 4.2. CdTe Thin Film

Since the 1950s, considerable attention has been devoted to the development and efficiency enhancement of CdTe-based solar cells. Single-junction devices with an optimal band gap of 1.49 eV and a potential efficiency greater than 20% were desired to realize CdTe solar cells commercialization [52,53].

Furthermore, researchers reported the first solar device with a significant conversion efficiency of 21.0% in 2014 [54]. Since then, the efficiency of CdTe thin film solar devices has increased significantly up to 22% [55]. However, this efficiency was not stable due to structural defects caused by grain boundaries and inter-grain dislocations. Another drawback was related to the reduced life expectancy for minority carriers known as one of the recombination factors, where it is often evident that carriers recombine [56].

#### 4.3. CIGS and CZTS Thin Films

Several decades ago, researchers extensively studied copper indium gallium selenide (CIGS) as one of the candidates for thin film absorbent materials. The scarcity of raw materials and the toxicity of this material led to advances in alternative materials such as copper zinc tin sulfur (CZTS). This material is an analogue of CIGS, possibly when Sn (IV), S (VI), and Zn (II) replace indium (III), Ga (III), and Se (VI), respectively [57].

The opto-electronic as well as structural properties of both of the above thin films can be further improved by replacing their constituent elements with readily available and earth-abundant compositions and nontoxic elements such as Sn, Sb, S, and CuS. [58]. For chemical treatment with hydrazine through non-vacuum particulate solution, the researchers reported a peak efficiency of 12.7%, thereby bringing the theoretical efficiency value to 32.4%. [59,60].

However, CZTS cells are prone to undesirably low voltages in the bulk material at the charge extraction interface as a result of recombination defects. Despite this, significant progress in the development of CZTS-based solar cells relies on finding alternative back contacts with low optical losses and maintaining low series resistance to render high efficiency for the entire device [61].

#### Tin Antimony Sulfide

In the quest to create environmentally friendly and earth-abundant binary compounds, antimony sulfide (Sb<sub>2</sub>S<sub>3</sub>) has emerged as a potential candidate thin film material compared to toxic Cd

or Pb. The material has a desired band gap of approximately 1.7 eV with a strong light extinction coefficient of  $1.8 \times 10^5 \text{ cm}^{-1}$  at 450 nm [62,63].

The above mentioned properties make antimony sulfide a suitable and ideal absorber material for thin film solar devices. Furthermore, reported super efficiencies for antimony-sulfide-sensitized solar cells reached about 7.5% using highly mesoporous device structures [64]. Several methods were used to fabricate Sb<sub>2</sub>S<sub>3</sub> layers including spin coating [65], chemical bath deposition (CBD) [66,67] and successive layer absorption [68]. Hole transport material (HTM) enhanced photo carrier extraction for fabricated solar cells [69].

Therefore, the crystal quality of Sb<sub>2</sub>S<sub>3</sub> determines the choice of HTMs, while some may poison the device stability in the long run, such as CuSCN, spiro-OMeTAD, or poly (3-hexylthiophene) (P3HT). The crystallinity of the absorbent layer is important to avoid the use of HTM. Further study showed that modification of planar solar cell based on TiO<sub>2</sub>/Sb<sub>2</sub>S<sub>3</sub>/P3HT planar solar cell reported 4.06% efficiency with CBD method [70].

Therefore, the search continued to find the desired crystal quality of Sb<sub>2</sub>S<sub>3</sub> and minimize dissolution; and rapid thermal evaporation (RTE) method was adopted. Further, an efficiency of 5.6% was obtained with the above method. Other methods were also used, in which, for conventional chalcogenide solar cells, annealing in a selenium atmosphere was the preferred method to combat defect passivation and realize improved crystallinity of the Sb<sub>2</sub>S<sub>3</sub> film. As a result, sulfurization and selenization methods were used to mitigate oxides and passive material defects [71].

## 5. Third Generation

This material represents one of the more promising advances in solar technology. Their application has yet to gain momentum as research into third-generation materials in photovoltaic devices continues.

### 5.1. Quantum Dots (Nanocrystal Based)

Nanotechnology has been a topic of interest to the science community for nearly a decade; Electronics, sensors, biomedical field etc. Various nanomaterials have been developed for many applications in Quantum dots (QDs) are nanoparticles of inorganic semiconductor materials. Their dimensions generally range from 1 nm to 10 nm corresponding to 10–100 atoms. Their energy levels are quantified by the confinement of electrons. The movement of electrons in the conduction band, valence band holes and/or excitons (S) is confined in all three spatial directions. Furthermore, various types of QDs are traditionally prepared from atoms in groups II-VI, III-V, and/IV-VI [72].

Quantum dot (QD) based photovoltaics absorb light from solution-processed nanocrystals and have versatile size-tunable band-gaps for fabrication in a wide range of substrates. These are a group of nanomaterials with good optoelectronic properties that are size dependent. Therefore, the band gap of colloidal metal chalcogenide nanocrystals always depends on the size of the quantum dots. Consequently, it promotes the efficient collection of near-infrared photons and the fabrication of multi-junction solar cells [73].

Quantum dot photovoltaics have significant advantages for their simple room temperature processing, fabrication, and air-durable operation. However, current challenges in this field are fundamental understanding of QD surface chemistry as well as limiting open-circuit voltage due to their inherent disorder in quantum dot films.

Although they have not yet realized large-scale industrial application, these technologies offer desirable device properties, earth-abundance structure reliance, and simple processing techniques. Ideal QD solar cells have been fabricated using PbS and/or PbSe. Interestingly, they have the potential for new applications in solar PV [75,76].

Another study reported on ligand free, methyl ammonium lead iodide (MAPbI<sub>3</sub>) QD solar cells with a PCE greater than 9%. These materials were synthesized in a porous silica (SiO<sub>2</sub>) matrix with a narrow nanopore size distribution. Synthesis parameter control translates to fine control over QD size along with spectral position over their electronic bandgap, preventing disorders that may affect the performance of as-built devices [77].

In the classical sense of the term, a nanometer-sized semiconductor crystal confined in all three spatial dimensions is called a quantum dot. Popular features of QDs include the generation of multi-excitons, known as MEG, and their tunability in optical and electronic states by minimizing size and quantum confinement effects. The MEG character in QDs allows the devices to rival the single junction Shockley-Queisser (S-Q) limit with 33% PCE. Three commonly used QDs that have been extensively studied over the last 3 decades include CdTe, CdS/Se and PbS/Se and are well represented in the light display market. With the resurgence of halide perovskite QDs, there is a potential new method for solar harvesting technology [78].

The practical situation for perovskite QDs (PQD) is similar to conventional QDs, with the use of organic capping ligands for growth control (steric hindrance) and new surface states. However, the surface form induces structural defects and affects the morphology and physical stability. Colloidal QDs are ideal candidates for large-area device fabrication via printing techniques that are more favorable than their organic and perovskite bulk counterparts. The highest PCE recorded for CsPbI<sub>3</sub> QD-based solar cells was 16% better than that of PbS QDs, indicating a large window of opportunity for next-generation QD photovoltaics [79,80].

## 5.2. Polymer Based Devices

Recently organic solar cells have attracted researchers as potential candidates for low-cost energy conversion devices. For a single-junction configuration, these cells reported a power conversion efficiency of 9.2% [81], which exceeded 12% [82] for a tandem structure. Another study focused on fullerene-derivative bulk hetero-junction (architecture) solar cells. An optimal thickness of 100 nm for this technology was reported from the most prominent features such as optical interference and recombination loss [81,82].

In addition, organic materials generally have a high absorption coefficient, although a significant amount of light is lost due to transmission between semi-transparent and reflective electrodes on organic solar cells. Nevertheless, the efficiency of organic-based solar cells can be significantly improved by more than 10% by understanding and reducing such losses [83].

### p-Conjugated Polymers as Hole-Transporting Layers (HTLS)

After the breakthrough in 1958, solar cells rapidly attracted attention due to their material abundance, cheapness, flexibility, and ease of manufacture. The processability of these materials has led to novel designs and device optimizations as well as innovative nano-engineered architectures and single-junctions that increase power conversion efficiency by as little as 17% and reach 18% [84,85].

M.H. Gharacheshmeh et al., reported on the use of textures and nanostructures to enhance the electrical conductivity of semi-crystalline conjugated polymers by water assisted (W-A) oxidative chemical vapor deposition (oCVD). The results revealed the charge transport between chains in the crystallite  $\pi$ - $\pi$  stacking distance and the interchain charge transfer integral. Interestingly, the use of W-A combined with a volatile oxidant, antimony pentachloride, reported electrical conductivities between  $7520 \pm 240 \text{ S cm}^{-1}$  for PEDOT thin films [44,85].

Controlling the synthesis parameters for the  $\pi$ - $\pi$  stacking distance decreased from 3.50 Å to 3.43 Å and reported an electrical conductivity improvement of  $\approx 1140 \%$ . In addition, the highest electrical conductivity also corresponds to a minimum Urbach energy of 205 meV, indicative of high

morphological order. Another characteristic was the figure of merit (FoM) for transparent conductors, which reached optimum maximum values of 94, 1.9× and 6.7×, respectively, and were higher than oCVD PEDOT grown without W-A and using vanadium oxytrichloride and iron chloride agents. The process is cost-effective because W-A oCVD is an all-dry one-step process, including mechanical flexibility, conformal coverage, and coarsely structured surfaces with minimal complexity or expensive transfer steps [44,85].

### 5.3. Dye Sensitized Based Solar Cells

Further studies were conducted specifically on dye-sensitized solar cells (DSSCs) as an emerging photovoltaic technology. This technology consists of key components that work synergistically for optimal cell performance, namely a redox electrolyte and a photo-anode counter electrode. Many single and polycrystalline semiconductor materials used in photo-electrodes include Si, InP and GaAs [86].

DSSCs have well-tunable optical properties (i.e., color and transparency), and are easy to fabricate as well as low-cost manufacturing processes, and ultimately are earth-abundant structures with application-specific properties for photovoltaics. Their best recorded efficiency in irradiated sunlight was only 10%. The main drawback of this technology is the choice of electrolyte which leads to photo-degradation and destabilization of the cell and thus shortens the life [86].

Recent studies have reported an improved power conversion efficiency of 14.3%. The stability of DSSCs has improved relatively over time. Moreover, it is imperative to discover and develop photo-electrode materials for the improvement of DSSCs, especially with respect to light absorption and electron transport. The suitability and suitability of materials in solar applications have a major impact on power conversion efficiency. In addition, TiO<sub>2</sub> is an ideal semiconductor photo-electrode material popular for DSSCs [87,88].

TiO<sub>2</sub> nanomaterial exhibits excellent textural properties such as high surface area (large number of contact sides to promote adsorption of dye molecules), and optimal electron transfer. It has been reported elsewhere that commercial TiO<sub>2</sub> exhibits a band gap of 3.0–3.2 eV [89].

### 5.4. Perovskite Materials

Extensive research has been ongoing for many years and recent progress has been made in polycrystalline films containing organic cations (A), inorganic cations (B), and halide (X) with the formula ABX<sub>3</sub>. Hybrid organic-inorganic materials are commonly known as perovskite materials—hereafter perovskite-based solar cells [90].

Desirable properties of perovskite materials include their long carrier diffusion length, band gap tenacity, low recombination loss, and availability of abundant materials (low cost). These exceptional properties allow PCEs to reach 25.5% efficiency while enjoying low fabrication costs and easy synthesis, as certified by the National Renewable Energy Laboratory (NREL). It is worth noting that the aforementioned are not available for conventional silicon-based solar cells [91]. However, parasitic absorption between the back reflector and the hole-conducting layer causes photocurrent loss for the perovskite absorption spectrum. In the quest to discover and develop perovskite technology, researchers reported on quasi-2D perovskite thin films, (C<sub>6</sub>H<sub>5</sub>CH<sub>2</sub>NH<sub>3</sub>)<sub>2</sub>(FA)<sub>8</sub>Pb<sub>2</sub>I<sub>2</sub>, where FA is formamidinium (FA), lead (Pb), and iodine (I). Moisture resistance and 80% relative humidity, reaching a PCE of 17.40%. Moisture resistance is attributed to ammonium salts. Recent research has shown that 2D perovskite is versatile and can achieve long-term stability as well as high efficiency for PSCs [92,93].

The development of third-generation perovskite solar cells has achieved efficiencies of just over 20%. Using Cl instead of I exhibits a continuous ability to fine-tune the band gap from 1.6 eV to 3.2 eV, and incorporation of low-band-gap materials improves efficiency. Polycrystalline films are formed from perovskite salts by precipitation methods with various polar solvents. In 2019, Noah et al., tested a

perovskite solar cell and achieved 23.3% efficiency through an interface passivating method to reduce recombination at the interface [94].

Additionally, perovskite solar cells have a significantly lower fill factor of 0.73, which results from the carrier shunt mechanism caused by non-uniform absorption (i.e., pinholes) and carrier-selective contacts (resistive losses associated with non-ideal carrier-selective contacts). More importantly, serious environmental sustainability issues limit the industrial use of these materials. It is worth appreciating the potential market entry point in which the perovskite acts as a top cell in a Si/perovskite tandem cell with a fundamentally large band gap [95].

## 6. Outlook

Greener technology involves a moderate method with the use of non-hazardous chemicals and organic acids and bases, resulting in significant savings in time and energy and also in the synthesis of high-value compounds for specific applications. Green processes are determined to produce no harmful by-products and allow tailoring for more precise control of particle size, shape and appearance in the nano-sphere. Bio-nanoparticle production is an environmentally friendly, low-cost, long-term approach to directly extract high-value nano silicon from naturally occurring agricultural wastes such as sugarcane bagasse, where Si occurs in the form of  $\text{SiO}_2$  [96,97].

### Future Prospects and Challenges

Figure 6 below presents schematic(s) for conventional (a) and inverted (b) solar cell device structures. It can be seen that the two proposed structures have several layers including a transparent conductive oxide (TCO), a hole-transport layer (HTL), an absorber layer, an electron transport layer (ETL) and metal. It is imperative to emphasize that these layers synergistically perform different functions to generate current from charge transport induced by incident light [98].



**Figure 6.** Schematic representation a (a) typical solar cell and (b) inverted solar cell architecture.

A transparent conducting oxide is traditionally chosen as the anti-reflective coat (ARC), as well as the conducting anodic electrode at the front of the cell. Generally, in silicon-based solar cells TCO layers with a thickness of 70 to 150 nm are desired in the absorbing material to allow adequate propagation of light and to minimize optical losses. Researchers have reported more than 90% minimum sheet resistance and smooth surface area when the TCO layer, mainly indium tin oxide (ITO) is between 80 and 180 nm [96-98].

Metallization, on the back/back side of the cell, has been found to be effective on gold (Au), aluminum (Al), and silver (Ag). Especially Gwamuri etc. [98] successfully reported that an ITO thickness of about 50 nm produces approximately 80% transmittance with high sheet resistance data, which is not desired for solar technology. Thus, a threshold of at least 70 nm must be confirmed to detect the synergy between smooth morphology, sheet resistance and transmittance.

**Recommendations:**

- Use alternative sources of solar materials such as biomass to reduce costs.
- Use green technologies, such as biomass (eco-friendly), renewable sources for solar materials.
- Use hybrid organic-silicon heterojunction solar cells.
- Use solar-grade silicon from silica (metallothermic reduction compared to carbothermic reduction process).
- Enormous scientific research efforts in the past were devoted to the development and optimization of the following;
- ETL, HTL, Perovskite composition, thickness, process and device structure.
- Advanced perovskite and non-toxic solar cells will lead to the development and discovery of new Pb-free perovskite light absorbing materials that are environmentally friendly and critical in the field of PVs. The new research area will be essential to realize stable and environmentally friendly perovskite PVs for real-world applications.

**7. Summary**

Crystalline silicon solar cells have been used for decades. Although this technology is at a mature stage, it is not yet economically viable for developing countries due to the high cost of raw materials and the large surface area required. Solar cell research based on heterojunctions (donor-acceptor) with staggered electronic band alignment called type-II configurations has the potential to overcome efficiency limitations in existing technologies. Despite this, it is still in its mature research stage and may be of use in the near future. Thin film technology is currently making suitable candidates for application-specific properties where buildings do not have permanent structures such as flat roofs, and this is a niche market for these solar cells. Interestingly, the performance of thin film solar cells has improved over the years as raw materials are used. Silicon is the most commercialized and the hybrid architecture allows the maximum utilization of this wire material as well as finding alternative sources which ultimately lowers the fabrication cost of these devices.

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