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Journal of Composites and Compounds

Recent developments and applications of nanocomposites in solar cells: a review

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ABSTRACT

These days, solar cells have attracted considerable attentions because they are environment-friendly sources of electric power. The present review is focused on composites and materials that are used in the solar cells field, including Si-based solar cells, dye-Sensitized solar cells (DSSC), thin film solar cells, Quantum dot solar cells (QDSC) and Perovskite solar cells (PSC). TiO₂ based nanocomposites, which are widely applicable in the solar cells are also reviewed.

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Peer review under responsibility of JCC Research Group.

ARTICLE INFORMATION

Article history:

Received 7 August 2019

Received in revised form 19 October 2019

Accepted 27 November 2019

Keywords:

Composites

Solar-cell

Perovskite

nanomaterial

Amorphous Silicon

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1. Introduction

These days, fossil fuels can be considered as a major energy source globally. The main fossil fuel sources from the industrial revolution (19th century) are gas, coal, and oil. Human communities use the fossil fuels to produce electrical and thermal energies that are necessary for different domestic and industrial applications. Electricity supply increases the productivity and access to principal services. This finally improves the

quality of human lives [1]. Nevertheless, the energy produced through these kinds of sources is not sustainable. The main issue about these kinds of fossil fuel sources (oil, gas, and coal) is that they have limited natural resources that will be depleted in near future. On the other hand, these abovementioned non-renewable sources emit CO₂ during the power production that is a type of greenhouse gases [2, 3]. The formation of thermal insulating layers would be accelerated by greenhouse gases in the higher atmosphere of earth. This will avoid common heat

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DOR: 20.1001.1.26765837.2019.1.1.7.6

<https://doi.org/10.29252/jcc.1.1.7>

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dissipation that is the result of global warming. Furthermore, the influences of global warming on agronomic productions and the ecosystems cannot be denied. It is known that rise in sea level is another result of global warming. Statistics show that the world population increases to 10 billion in 2050. If this happens, carbon emissions should be limited by 75% in 2050 to decline the rise of 2 °C in the earth temperature [4]. Clean energy sources should be used to limit the environmental hazard considerably. The key step to achieve this aim is the use of environmentally friendly sources such as solar energy, biomass, geothermal energy, hydropower, biofuel, and wind power. Although the majority of these mentioned clean energy sources are rather non-polluting, solar energy can surely be considered the most attractive energy source due to its abundance, cleanness, and safety. Reports exhibit that if solar cells with the efficiency of 10% cover merely 0.1% of earth's crust, the immediate need of energy may be met worldwide [5]. Consequently, to meet the increasing need of energy around the world, solar energy can be taken into account to play a crucial role in this regard. To date, solar energy has been applied chiefly to produce electrical and thermal energies. Solar light can be collected by technologies, which can work based on solar energy. The collected solar light can produce heat immediately. Photovoltaic is the technology that can transfer the solar energy to electricity. Hence, solar cells can be called photovoltaic devices. This technology is classified into three generations (a) crystalline silicon based SCs, (b) hybrid and amorphous silicon based, GaAs-based or CuGa thin films selenide (CIS/CIGS), cadmium telluride (CdTe) based, and (c) materials such as metal oxide semiconductors with wide band-gap TiO_2 , Nb_2O_5 , SnO_2 , ZnO , and etc. [6-9]. The main instances of the newest generation of solar cells are quantum dots that are sensitized to dye, and organic solar cells, which makes them more effective for using the sunlight. The virtue of this novel generation is based on different kinds of novel materials are used to make them instead of conventional silicon. The favorite third generation solar cells can be perovskite based solar cells, a solar cell design that uses quantum dots as the absorbing photovoltaic material, and dye-sensitized solar cells (DSSCs). All of these different types of solar cells have both advantages and disadvantages. Efficient photovoltaic performance is one of the benefits of the first generation solar cells, whereas they are not adaptable enough. In addition, their considerable processing cost is their main limitation. The complex processing and toxic effect of second generation solar cells make them difficult to be used as photovoltaic devices, however, the photo-electric conversion efficiency of them is high. Now, dye-sensitized solar cells (DSSCs) are attracting attention scientifically and technologically, since they are easy to fabricate, extremely effective and inexpensive substitute for common photo-voltaic devices. The energy crisis resulting from the constant consumption of common energy resources, such as oil, natural gas and coal can be resolved by sustainable sources of energy like solar cell modules. Solar cells have been emerged to harvest and convert solar energy to electrical energy to provide an invaluable source.

2. Photovoltaic effect and principle of solar cell operation

The photovoltaic effect was observed for the first time by Becquerel through conversion of solar radiation. Photovoltaic effect is commonly known as the emergence of an electric voltage between two electrodes that are attached to either a liquid or solid system which is radiating light onto the system [10]. The modern age for photovoltaic devices commenced when Chapin developed the initial single-crystal silicon solar cell in 1954. The first Si solar cells with the efficiency of 6 % were fabricated at Bell Laboratories. In 1960, their efficiency was increased to 14% with a better technology [11]. A solar cell is able to convert light directly into electricity (Fig. 1).

Fig. 1. (a) The equivalent circuit and (b) schematic structure of a solar cell device.

The electric power produced by both bias voltage and electric current is the result of the produced shining light on a solar cell. During the process, firstly, electron and hole carriers are generated through the incident photons absorption. Secondly, the assembly of these carriers by the p-n junction inhibits the recombination made by a p-n junction to separate the electrons and holes spatially. With the short-circuited solar cell, (such as the solar cell and an emitter are connected), carriers generated from light would flow through the external circuit. It would be worthwhile to make an electrically equivalent model (Fig. 1a) to find out the electronic behavior of a solar cell. The behavior of an ideal solar cell is similar to diode, which can be modeled, with a diode in parallel mode via a current source. A p-n junction would be the basis of the diode formation and can make a less considerable electric current under reverse bias ($V < 0$) in the dark condition than that under forwarding bias ($V > 0$). PV devices show such rectifying behavior.

Upon illumination, photocurrent is produced, which is divided into two paths that go through the diode and load, respectively. It is interesting to say that the density of photocurrent is related to the illumination intensity. The current density related to each pathway is based on the level of illumination, the resistance of the diode and the load. For loads with higher resistance in contrast to the diode, higher proportion of the photocurrent flows over the diode. This results in a smaller current through the load and a potential difference between the cell terminals which leads to photo voltage provision by diode.

Solar cell generates the photocurrent which is dependent on the incident light, the active area of solar cell, semiconductors absorption coefficient, band gap, and the efficiency of charge collection [12].

3. Si-based solar cells

Silicon and silica are widely studied by researchers [13-18]. Generally, although Si is not an ideal material for photovoltaic conversion, it has been used in the production of solar cells in a large-scale. The low absorption coefficient of photons results in thicker cells in an indirect band gap semiconductor. Nowadays, crystalline Si has a 90% market share in almost equal shares for cast silicon and single crystal. In addition, amorphous Si has a 9% higher market share. Prior to the appearance of photovoltaics, high quality Si was produced in large scale for semiconductors. Thus, it is expected that silicon plays a dominant role in the market of world [19]. Estimates show that photovoltaic material production will be increased for next years along with the growing significance of multi-crystalline silicon. At present, Mono-crystalline Si can be used to develop the high efficiency solar cells. With the development of absorption in the junction area, wafers that are thinner than 200 μm are also used. The cost of viable Si is going to increase significantly in close future. Thus, it is expected that the use of thinner wafers would be increased in the future.

3.1. Amorphous Si solar cells

Varied affordable polymers as well as other elastic substances that consume a smaller quantity of energy are able to be applied in the manufacturing process of the amorphous silicon solar cells. This is due to the fact that their processing can be performed at a low temperature [20]. Consequently, not only the price of the a-Si solar cell is relatively reasonable, but also it is widely accessible. The fabricated silicon material of a cell without a fixed structure of atoms in the non-crystalline structure and lattice configuration can be defined as the “amorphous” in the field of solar cells. These are formed via coating the doped Si to the backside of the substrate/glass plate. They appear silverfish on the conducting side and dark brown on the opposite side (reflecting side) [21]. The key problem of a-Si solar cell is the weak and virtually unstable efficiency. It is acceptable that the cell efficiency at PV module level falls automatically and the range of variation for efficiencies of commercial PV modules is in the range of 4–8%. Moreover, a-Si solar cell can act at high temperatures and they are the right option for the variable climate situations [22].

3.2. Crystalline silicon solar cells

Crystalline silicon SCs contain monocrystalline and polycrystalline technologies. They enjoy a photovoltaic market share of nearly 90% globally, thus they can be considered the most substantial photovoltaic technology. Currently, monocrystalline and polycrystalline silicon solar cells with common surface field process of Al-back have shown the efficiency value of 18.5% and 19.8%, respectively [23–26], which is very similar to the limit of the common production line of crystalline silicon. The solar cells are made of crystalline silicon produce PV power that includes the following physical processes: (i) absorption photon resulting in the excitation of the pairs of electron hole and (ii) dissociation and transportation process to the external electrodes for electron–hole pairs [27–32]. Thus, generally the technology of high efficiency crystalline silicon solar cell include: 1) the design of a modern cell structure, 2) the optimized-light absorption, 3) the efficient assembly of photo-generated carriers and 4) the elimination of the recombination loss of photo-generated carriers as well as the area reduction and the electrode resistance. A categorization of crystalline silicon solar cells with high efficiency include intrinsic heterojunction thin-layer cell (HIT), interdigitated back contact cell (IBC), heterojunction interdigitated back contacts solar cells (HBC) and passivated emitter rear cell (PERC).

3.3. Monocrystalline silicon solar cells

Czochralski process, is a process in which single crystals of silicon would become mono crystalline solar cell [33–35]. Si crystals are sliced from the large ingot. Their production needs exact processing since the recrystallizing process of cell is not cheap and includes several processes. The efficiency of silicon solar cells with mono-crystalline single-crystalline structure is between 17–18% [36]. Amorphous Si (a-Si) PV modules are the elementary solar cells that are first to be manufactured industrially.

4. Thin film solar cells

It is possible to reduce the cost of photovoltaics production. More affordable thin-film technology, which involves different semiconductors such as CuInGaSe₂ (CIGS), CuInSe₂ (CIS), CdTe and CdS, can replace the wafer-based solar cells. Many appropriate options can be applied to produce the thin film second-generation solar cells. Recently, thin-film Si and amorphous silicon (a-Si) have also been suggested to be suitable candidates [37]. It is possible to remove the silicon wafer

by using thin-films. This will reduce the material costs significantly. An increment in the unit of manufacturing from a silicon wafer (the order of 100 cm² compared to a glass sheet of 1 m²) is another advantage of this technology. The matured second-generation “thin-film” technology will surely provide domination by the costs of the component materials in the future. In this regard, they are encapsulants including top cover sheet. Nevertheless, there is a limit for the cost of constituent materials. It cannot be below a minimum limit. Cu_xS and CdTe are promising materials as absorbers in heterojunction solar cells, which have the direct band-gaps of 1.2 eV and 1.45 eV, respectively. Under sunlight radiation, the energy gap of the Cu_xS and CdTe absorbers is about optimal value for maximum efficiency. Thin films are suitable for preparing photovoltaic cells with great efficiency due to the 8 direct transition types of their band structure, which can present excellent absorption coefficients. In association with other p-type semiconductors, CdS that have the energy gap value of 2.54 eV and as a native n-type semiconductor) can be used as window layer. If the thickness of device is optimised, the conversion efficiency will be improved by CdS.

4.1. Thin-film crystalline Si cells

Since last years, companies such as Kaneka and Astropower took promising steps towards the thin-film monocrystalline silicon (mc-Si) solar cell with 10% efficiency as well as thin-film large-grained poly-Si solar cell with an efficiency of 16%. These corporations made significant developments regarding crystalline Si thin-film solar cells [38]. At present, the efficiencies of poly-Si cells with large grains can be enhanced from 15%–17% to nearly 18%. Furthermore, the efficiency is expected to increase to 20% in the future, since there is no limit for monocrystalline Si thin-films by material constraints. Considering the cost of crystalline Si thin-film solar cells, the association of glass as a substrate and crystalline Si offer the most economical method for large-area monolithically integrated modules. With this in mind, the efficiency of this technique is not as high enough as those produced from other processes, which is the most significant drawback for this method. To produce thin film solar cells with reasonable price and high efficiency, transferring thin films of monocrystalline-Si to glass is an alternative method.

5. Tandem cells

If the energy absorbed by photon is slightly higher compared with the cell bandgap, energy losses in solar cells can be mainly ignored. The tandem or multijunction cell (multiple cells with various bandgaps) is a direct application of this effect. Each cell converts a narrow range for photon energies near its bandgap.

Most recently, the tandem cell is produced commercially. Double and triple junction cells based on Ge/GaAs/GaInP have been used for use on spacecraft. They exhibit about 30% terrestrial conversion efficiencies [39]. Good resistance to radiation damage and low temperature coefficient are their main advantages. Besides, they are ideal for high concentration optical systems applications. Tandem cells can be used to enhance the reliability and performance of thin-film amorphous silicon cells so that they get fixed efficiencies up to 12% confirmed for Ge:Si:H triple junction cells [37].

6. Dye-Sensitized Semiconductor

The modern era of work on organic solar cells has commenced in 1960s. The progress was due to the clarification of the mechanism related to spectral sensitization of semiconductors through absorbed monolayers of dye molecules. It is well-known that Coulomb interactions between adsorbed molecules and charged defects play an essential role

Fig. 2. Illustration of the OSC working mechanism.

to create light harvesting that is the result of a distribution of ionization energies of the adsorbed molecules [40]. Depending on the surrounding environment of the molecule, which absorbs the light, polarization effects and other corrections can reduce the ionization energy to an acceptable value for transformation of electrons [41]. It is necessary to find out the primary processes, depending on relations of the energy levels. Charge carrier injection, transport, trapping, and photogeneration, are based on these energy levels. The research on dye sensitized devices using porous TiO_2 has shown promising results. The monolayer dye molecules are excited after the photons absorption on porous TiO_2 . If the energy of excited state is higher than the lower edge of the conduction band of TiO_2 , electron transferring can occur (from the dye to the semiconductor). A redox species dissolved in an electrolyte is needed for completing the cell, which is able to fill the distance in the porous matrix. Moreover, it gives an electron to the oxidized dye. Then, the mediator redox species is oxidized. Next, it can be reduced at the metallic cathode of the cell. To replace the p/n junction, organic materials can be applied in soft junction cells (organic cells). Polymer/fullerene blends, interpenetrating polymer networks, devices based on small molecules can be used. There are no limits for the choices and large area cheap cells are very attractive.

7. Organic solar cells

Organic solar cells (OSCs) have attracted the attention of researchers significantly, as they are not heavy, flexible and easy to fabricate (Fig. 2). Organic solar cells need to attain their potential Shockley-Queisser (SQ) power conversion efficiency (PCE) limit (approximately 33%). However, the enhancement of PCE (from <1% to 14%) in the recent decade has presented them as favourite solar-cell technologies among other solar-cells [42]. Organic semiconductors (as donor and acceptor materials) having optical and electrical characterizations are responsible to determine the performance of device and are able to be used in organic photovoltaic (OPV) devices. Large amounts of raw materials have been developed through adapting the structures in side chains and backbones by researchers, for optimization of the crystallinity and band gap. This was done with the goal of obtaining a well-matched donor/acceptor blend system, great charge transportation properties and the excitons dissociation. The power conversion efficiency of an organic solar cell can be controlled by photovoltaic properties of a bulk Hetero Junction OSCs. It is acceptable that the conjugated organic molecules selection in the nanostructure of a photoactive layer can induce morphology changes and this, can affect photovoltaic properties of a BHJ organic solar cell. With the improvement in extremely sensitive microscopy techniques and light sources, quantification of microscopic information has greatly improved. Methods such as transmission electron microscopy (TEM)

Fig. 3. Demonstration of device structures in OSCs: (a) single-layer, (b) bilayer, (c) BHJ, and (d) ordered-heterojunction.

and atomic force microscopy (AFM) have enhanced the evolution characterization of design and development of materials structurally. Recently, with the characterization improvement of an active layer via X-ray scattering, scientists are able to plan devices through ideal conditions of processing with the use of new conjugated organic materials molecular structures for the OSCs with optimal configuration (Fig. 3). Since the materials should be selected with respect to their function, the hole or electron transportation interlayers, a flexible Polyethylene terephthalate/graphene-substrate or an ITO-glass, a photoactive layer, and metal electrodes, can constitute the structure of a traditional OSC device. The excitation of electrons can occur from the highest to lowest energy level of their HOMO when photons of solar energy can be absorbed by organic materials in the photoactive layer, which can lead to formation of an exciting state (electron-hole pair) bounded through attractive forces of Coulomb. Maximum photons from the solar spectrum of energy need to be absorbed by active-layer materials in order to fill a good population of excitons of the LUMO level. In fact, a right blend of organic species, is required to absorb the majority of the photons from the spectrum of solar energy including the NIR region Dielectric constant from 2 to 4 for organic materials can increase bonding energies in excitons. They should be diffused to a nearby interface of D/A for separation into free charges. The charge transfer (CT) excitons can be generated from photogenerated excitons owing to high binding energy at the D/A interfaces. Subsequently, dissociation occurs into courtesy of free charges of an in-built electric field made via an organic combination function offset of the acceptor/donor. Thus, free holes as well as electrons can be transferred through particular domains to create a photocurrent [43].

8. Quantum dot solar cells (QDSCs)

During the past few years, QDSCs have achieved popularity due to an increase in ECE of PV devices (about 42%) above common Silicon-based SCs and even S-Q limits. Three different methods, including (1) schottky SCs [30], (2) semiconductor nanostructure-polymer SCs [44], and (3) solar cells based on QDs [45] can be used to incorporate Semiconductor nanocrystals in PV cells. QDs have attractive properties such as excellent optic absorption coefficients (α , about $1,00,000 \text{ cm}^{-1}$), MEG, large dipole moments, solution process ability, high molar extinction coefficient, bandgap dependent on size, extinction coefficient, and photo-stability. QDs can be widely regarded in PV applications due to mentioned properties [46]. QDSSCs and their different components have been shown in Fig. 4(a). Furthermore, Fig. 4(b) shows charge carriers disorder between varied constituents. QDs which can be considered as light absorbents [47], lead to the production of charge carriers with transmit across elective local phases in QDSSCs. Incident photons generate electrons. The generated electrons transfer to a semiconducting

Fig. 4. (a) Schematic illustration of QDSSCs with their different components; (b) charge carriers shuffle between various components.

oxide layer (zinc oxide, titania, tin oxide [48], etc.) with QDs attached. Next, the transmission of transported electrons to the conducting ITO/FTO glass will take place. This supports the oxide layers with nano structure. Next, QDs achieved their initial state again via a solid/liquid electrolyte, which contain a reversible redox couple. The counter electrode (CE) can be made from metal and it can be semiconducting. It should not have slow kinetics for the electrolyte redox couple. Effective QDSSCs need an excellent fill factor, high incident of photon-to-current efficiency (IPCE) and great open circuit voltages.

Recombination processes and the carrier mobilities can be considered to have a considerable impact on the effectiveness of Quantum dot sensitized SCs. Thus, it is accepted that the efficiency of electron collection in these cells can be dependent on morphology and the nature of the transporting phases of the charge carriers. The MEG phenomenon (as one of the most important benefits of QDSSCs), occurs in semiconducting nanocrystals, which provides the advantage of the use of hot carriers for the system. Pairs of electron holes can be generated by the MEG phenomenon and it can result in a single photon absorption in at least two times of band gap energy of the sensitized material. For PV applications, dyes are being substituted by QDs, since MEG provides much higher ECE (about 44%) than common DSSCs (in theoretical point of view) [49]. Moreover, the sensitivity of QDs to light, simple synthetic method and tunability of light absorption, make them great light absorbers. Besides, semiconducting nanocrystals enhance the robustness of the cell. The photovoltaic characteristics proved that the use of metal oxide (e.g. Cobalt Oxide), as counter electrode materials, and the CE can reach a PCE of 6.02% for QDSSCs, which was illustrated by Li et al. [50] in 2019. This technique increases the efficiency in contrast with common Cu_2S CE (32.7%). Badawi et al. [51] synthesized Ternary alloyed $\text{Cd}_{1-x}\text{Co}_x\text{S}$ (in which x can be 0, 0.1, 0.2, 0.3 and 0.4) QDs onto TiO_2 nanoparticles electrodes to use in photovoltaic applications directly. Among them, the alloyed $\text{Cd}_{0.9}\text{Co}_{0.1}\text{S}$ QDs sensitized solar cell, exhibited the best photovoltaic capability, which is because of the harmony that exists between the energetic levels of the QDs sensitized solar cell components and the improvement in the absorption of solar spectrum. The photovoltaic valuation of the collected QDs sensitized solar cell, show high reproducibility, and sensitiveness that undercut on-off solar illumination. Mahanandia et al. [52] synthesized monodisperse $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) QDs through solvothermal method in 2018. They found that CZTS QDs are extremely pure with the optical band gap of larger than bulk CZTS $\sim 1.5\text{--}1.6$ eV (1.89 eV). This is because of the quantum confinement, which makes them suitable for solar cell applications. Moreover, the optical absorption spectra of CZTS QDs show a blue shift to a higher energy.

9. Perovskite solar cells

In contrast with the common silicon and thin film SCs, perovskite solar cells have many advantages, which have the formula of ABX_3 , in which A and B are cations of different size and X denotes a halogen e.g. Cl^- , Br^- , I^- . Among the solar cell research community, perovskite solar cells are recent finding, which have many benefits compared to thin film based and conventional Si solar cells. Conventional silicon based solar cells must be processed under high temperatures ($>1000^\circ\text{C}$) and they require many processing steps, high-priced and vacuums facilities [53, 54]. They usually have efficiency up to 31% [55]. However, we have to consider current problems with perovskite solar cells i.e. their durability and stability. The material degradation takes place over time. Thus, a decrease in overall efficiency is expected. Consequently, to bring these cells into the market place, more research is required. Table 1 illustrates the Perovskite solar cell efficiency at various temperatures.

Park et al. [56] reported the principles for the design of a high-power PSCs for inside light applications having low-intensity, with a special emphasis on the electron transport layers (ETLs). Their results showed that the procedure of power generation of Perovskite solar cells when it is under halogen lights and a low intensity LED is not similar with the 1 Sun standard test condition (STC). In comparison with the c-TiO_2 (the compact-titania) PSC, c-TiO_2 PSCs was able to generate much more power than mesoporous-Titania (m-Titania) PSCs under low-intensity condition (200-1600 Lux) situations, although a PCE was gained from the PSC based on m-Titania under STC. Methyl ammonium (MAI) and $\text{Pb}(\text{NO}_3)_2$ was used in perovskite film by SupaChoopun (as starting material). Spin coating technique was used for deposition of precursor of

Table 1.

Efficiency of Perovskite solar cells (DSCC) at various temperatures

Temperature ($^\circ\text{C}$)	Efficiency (%)
30	9-10
35	9-10
40	8-9
45	8-9
50	8-9
55	7-8
60	8-9
65	7-8
70	6-7
80	5-6

perovskite in p-i-n perovskite solar cell construction. It was found that its power conversion efficiency, compared to perovskite film (made by traditional Lead (II) iodide), is weak. Nevertheless, toxic solvent operation with an easy evaporation (dimethylformamide) for green production of perovskite solar cells was removed by this process. The influence of non-uniform and pin-hole of perovskite films, weak coverage, incomplete formation and weak coverage result in their low performance. To replace Lead (II) iodide material for PSCs, they found $\text{Pb}(\text{NO}_3)_2$ as a substitute material [57]. Mufti et al. [58] studied the influence of temperature on the morphology of nanorod (NR) and optical properties for $\text{CH}_3\text{NH}_3\text{PbI}_3$ perovskite solar cell device application. Zinc oxide NRs were prepared via a hydrothermal approach on the ITO substrate. The structure of solar cell was composed of ITO/ZnO oxide seed layer/zinc oxide NRs/ $\text{CH}_3\text{NH}_3\text{PbI}_3$, and zinc oxide NRs, (as nano shaped stem layer) where perovskite crystals form.

10. Nanocomposites in perovskites solar cells

In order to improve the perovskite films morphology with regard to device performance, crystallization kinetics, and crystal growth, the addition of nanoparticles in perovskite based solar cells was applied. Different nanoparticles because of their different physical and chemical properties, can play an essential role in the generation of perovskite thin film. A method, which is accepted extensively, involves mixing poly (3,4-ethylenedioxylen- thiophene): poly (styrenesulfonic acid) (PEDOT: PSS) and metal NPs, active layer or as cathode interfacial materials. It is well-known that new metallic structure of NPs are able to show a high efficient absorption band in the UV-Vis area. It lies within the optical absorption band of the conjugated polymers which are applied in the active layer of organic photovoltaics. To promote absorption, plasmonic metallic nanoparticles (NPs) can be used either inside the active layers of OPV devices or buffer. This can enhance the optical thickness of Organic Photovoltaics materials in order to harvest light [59-61]. Considerable reduction of both the quantity of lead, which is present in the device structure and the thickness of the perovskite film can be seen by Plasmonic nanoparticles. They can ensure a broad-spectrum light absorption simultaneously.

11. Application of nanomaterials in solar cells

The nanoscale materials have high surface area to volume ratio. This property offers other wonderful optical, physical, and chemical properties. Several instances of physical extended capabilities of nanomaterials are as follows: (i) considerable reduction in the possibility of recombination of charge carriers which is because of the fact that light-generated carriers travel shorter path (ii), energy bandgap can be inter-changeable and flexible by changing the dimensions of nanoparticles, and (iii) increased optical path because of several reflections [62]. Due to these properties, nanomaterials are very interesting for PV applications. In fact, nanomaterials present flexible materials in PV assemblies which have the capability to convey solar heat by new approaches [63]. Therefore, the potential of PV devices for light trapping and the collection of photo-carriers can be improved greatly [64]. Furthermore, the manufacture of novel materials can be enhanced by synthesis approach. Take passivated nano-scale crystals and monodisperse as an example: they show optoelectronic properties, which results in more control over shape, composition and structure [65]. In other words, nanoparticles are able to reach the fundamental principle of PV devices for the optimization level so that the optic absorption of the active/ sensitizer layer can be increased and the loss of charge carrier is prohibited throughout transportation. To find out the best association of the nanomaterials to

increase both the performance and the properties of DSSCs, researchers have had many experiences. This can be achieved by using nanocomposite materials. As such, they are performing expansive studies using various composite nanomaterials for DSSCs. TiO_2 is attractive, because of its high chemical stability and dye adsorption ability. Moreover, TiO_2 enjoys longer electron lifetime and high surface area [66, 67]. Its considerable electrical and optical properties and low-priced production also cannot be denied. It is worthwhile to mention that it can be harmonized for several physical properties [68]. An electrolyte and injected electrons can be recombined, which is the essential loss path in the DSSCs. This recombination increases the dark current which can decrease the device performance finally [69]. Mesoporous structure TiO_2 experiences low electrical conductivity, which is the result of more interfaces between particles in spite of the fact that it has great dye adsorption ability. It should be said that electrolyte penetration into pores can elevate the recombination reaction, and these issues promote the development of novel morphologies or nanostructures of TiO_2 , which have great dye adsorption capability as well as electrical conductivity [70]. Nanostructures such as nanotubes, nanorods, nanowires, and hollow spheres have been made for efficient DSSCs. Scattering of light in a layer of TiO_2 nanofibers can extend optical path length from the wavelength of incident light. This will be able to extend optical path length. Therefore, we can see intense light absorption for nanofibers in the visible region [71, 72]. To improve the light absorption of TiO_2 films and decrease the recombination for holes and electrons, the adjustment of novel metals can play a significant role in this regard (for dye-sensitized solar cell).

Zhao and Dong et al. [73], compared the power conversion efficiency (PCE) of composite photoanode of TiO_2 nanofibers/ nanoparticles (NF/ NP) soaking in AgNO_3 solution in comparison with the photoanode without Ag adjustment. Their results showed that soaking in AgNO_3 solution increased the PCE of composite by 18.0%.

Hong et al. [74], developed the device which was fabricated from the perovskite solar cells. As an electron transporting material, they applied the electrospun reduced GO- TiO_2 composite nanofibers. This device showed an 3.27 % and 1.84% increase in power conversion efficiency in comparison to mesoporous- titanium oxide and pristine- titanium oxide nanofibers, respectively. ZnO nanofibers web was used by Biji et al. [75], as photoelectrode. Using these nanofibers, they designed and developed a stainless flexible mesh-based quasi-solid DSSC. According to the photovoltaic performance examination, they exhibited overall solar conversion performance of 0.13% for the created DSSC with following characterizations: fill factor: 32.77%, short-circuit photocurrent density: 28- μA and open-circuit voltage: 0.321 V. In order to develop the TiO_2 efficiency in the dye-sensitized solar cells as a photoanode, Motlak et al. [76] came up with nanofibrous morphology and Cd-doping and empirical results revealed that Cd ions that interfere with crystalline TiO_2 nanofibers can make an enhancement in reduced re-bonding between the charge carriers between the working electrode and electrolyte in the barrier area, the transportation of the charges and the absorption in the visible spectra. In other reports, Chou et al. [77], prepared the TiO_2 nanofibers including silver (Ag) nanoparticles (NPs) and graphene oxide (GO), via combination of sol-gel technique and electrospinning method. Their results showed that $\text{TiO}_2/\text{GO}/\text{Ag}$ NF or TiO_2/GO NF (as an extra layer) can increase η (40% or 16%, respectively) with respect to standard DSSC. Moreover, the additional composited TiO_2 NFs layer can prevent recombination of electrons between the interface of electrolyte and TiO_2 electrolyte. This can result in the increase of carrier transmit prohibition. The energy barrier can be improved by the insertion of nanowires at the interface of electrolyte and semiconductor. Besides, the transportation of the electron to the electrolyte can be decreased. This, consequently, can reduce the density of surface traps. Increase in the properties of electron transmission of TiO_2 remarkably would be possible by one-dimensional nanotubes. Liu et al. [78], (2018) prepared nanowires directly on the

conductive substrate of glass by two-step solvothermal reaction. They used them as photoanode and found PCE of 5.30%. An increase in the PCE up to 8.28% was exhibited when associated nanowire arrays (NWAs) collected by monocrystalline rough-surface rutile-TiO₂ nanowires have been fabricated via straightforward solvothermal methods [79]. The effect of combining Ag nanowires TiO₂ nanofibers (NFs) and Ag nanowires (Ag NWs) nanofibers into a tri-layer photoanode DSSCs was examined by Kumari et al. [80]. They found that tri-layer TiO₂ P25/P25/P25 photoanode is 45.6% more efficient than the reference DSSC (6.69%). It is known that nanotubes with one-dimension greatly advance the electron transportation performance of TiO₂. As expected, there are lower contacts between crystals in TiO₂ nanotubes compared to NPs, resulting in an increase in the speed of electron transportation, and the electrical conductivity can be improved by Nanotubes, as they prepare the smooth electronic path for injected electrons. The recombination reaction can be reduced by the fast electron transmit considerably. To avoid complex synthesis, carbonaceous nanocomposites with TiO₂ have been suggested to get DSSCs with high efficiency. Liang et al [81] synthesized TiO₂ nanotube arrays with 2 appropriate diameters and heights directly on the fluorine-doped SnO₂ surface through applying the aqueous TiO₂ sol-gel methods and tubular photoresist templates. A considerable PCE ~14 % was indicated by the fabricated PVSCs. Liu et al [82], used TiO₂ gel to prepare the TiO₂ nanotubes (TNTs) via hydrothermal method. Ag nanoparticles (Ag-TNTs), then, were used to modify the synthesized TiO₂ nanotubes via in-situ photo deposition reaction. The filling factor (FF) for prepared photoanode was reported to become 53.63% and the efficiency (η) of 7.2% was obtained. Rho et al. [83], studied the performance of DSSCs with the investigation of the influence of Titania nanoparticles/Titania nanotubes-silver nanoparticles (TiO₂NPs/NTs-Ag@TiO₂ NPs) composites. Because of the enhancement of electron transport via nanotubes, the power conversion efficiency (PCE) has increased as much as 0.74% with TiO₂ NPs/NTs in comparison with TiO₂ NPs film merely. Hydrothermal methods and facile sol-gel were used to prepare TiO₂ nanotubes (TNTs) and TiO₂ nanoparticles (TNPs), respectively. For the TNPs layer coated with TNTs (combined photoanode), the power conversion efficiency, was reported at 5.43%. This quantity was in contrast with the individual ones [84]. Carbon allotropes have remarkable properties such as excellent stability against electrolytes, great electron mobility and high electrical conductivity [85]. Especially, graphene and carbon nanotubes have considered being effective fillers for PE of DSSCs, which is due to their good ability to harvest light and good electron mobility [85, 86]. A better output voltage can be achieved by applying CB /TiO₂ as a PE. This is because of the conduction band energy level of CB /TiO₂ film which can be increased by the higher conduction band energy of CB C [87]. As a substitute for traditional platinum counter electrodes applied in DSSC applications, Jaafar et al. [88], proposed counter electrodes based on CB-TiO₂ composite. Their empirical results indicated the impact of the CB-TiO₂ composite on the photovoltaic performance, which can be through increasing the electro catalytic activity. It is expected that as the quantity of CB increase, the increase in the surface area would be unavoidable. This will enhance the catalytic activity that can lead to low charge-transfer resistance (R_{CT}) at CB electrode/ the electrolyte interface. Viable substitute counter electrode (the reformed photoanode along with natural dye sensitizers) can produce the highest energy conversion efficiency (2.5%). Rahman et al. [89], prepared the counter electrode by a facile method. This counter electrode (an electrode of nitrogen doped acetylene carbon black decorated palladium nanoparticles) shows a PCE of 7.95%, (higher than the cell fabricated of Pt counter electrode). At interfaces of electrolyte/TiO₂ and dye /TiO₂ in dye-sensitized solar cell, recombination can appear [90]. Thus, to reduce this reaction, 1-D nanostructure photoanode, has been employed. Carbon nanotubes (e.g. SWCNTs and MWCNTs) have good electron mobility. This favorable

member presents an efficient transportation path for injected electrons [91]. High conductivity of CNTs as well as high performance plays an essential role in the DSSCs present an efficient transmit path [92]. The use of CNTs instead of carbon black can cause a better upper limit conductivity and less percolation threshold in TiO₂/CNTs composites. It is understood that particles with large aspect ratio possess low threshold than spherical structures because of a higher excluded volume with the similar weight. Thus, reducing the percolation threshold can be a crucial concern in order to gain cost-effective conductive composite material [93]. Graphene can be regarded as a great additive material for the PE of dye-sensitize solar cells, because of its excellent electron mobility and surface area and tunable bandgap. Furthermore, to present an efficient charge transportation path for the injected electrons, 2D-graphene sheet is an ideal option [94]. Many empirical results exhibit that graphene-based PEs have better PCE in contrast with the carbon particles and CNTs [95–98]. This is because of the limited overall efficiency of DSSCs, which is the result of the better charge recombination with electrolyte versus graphene. This limitation of the total efficiency of dye-sensitize solar cells can be because of the feeble interaction of the spherical TiO₂ nanoparticles with CNTs. In contrast, single-sheeted graphene have higher contact with TiO₂ nanocrystallites. The fabrication of hybrid TiO₂/reduced graphene oxide composites with many dimensional and self-collected structure for dye-sensitize solar cells, have been investigated by Manikandan et al. [99]. To quicken the electron transportation channel within the TiO₂ matrix, GO in the TiO₂ matrix can be loaded. This then can result in higher photo conversion efficiency in comparison with neat TiO₂. 8.62% versus 6.3%. Graphene Oxide nanosheet suspensions which are coated on a glass plate and Titanium Tetra Isopropoxide (TIP) was used to prepare TiO₂-GO nanocomposite thin films of several grades via a spin coating method by Timoumi et al. [100]. After the evaluation, optical absorption data exhibited the reduced band gap energy along with enhancing dopant quantity (3.62 to 1.40 eV), which is due to the hole or/and electron trapping at the acceptor /donor levels in the TiO₂ band structure. Spin coating technique and liquid phase deposition were used to prepare TiO₂ films, which are Graphene-coated. Next, they were employed as photoanode of dye-sensitized solar cell. The highest value of power conversion efficiency of DSSC (η = 1.47 % and Voc = 0.66 V), is the outcome of Coating TiO₂ films with graphene layer [101]. The perfect decoration of rGO (1.0 wt. %) in photoanodes develops electron lifetime, charge transport, and the biosensitizer loading. Besides, it can reduce the recombination of the Bio sensitized solar cells (BSSCs) significantly. Reduced graphene oxide (rGO) and mixed phase TiO₂ nanorods (NRs) can be used to make Nanohybrid photoanodes, which is fabricated via one step hydrothermal method [102]. TiO₂ photoanode sensitized with dye molecules was loaded by different amount of graphene nanoribbons (GNRs) by Akilimali et al. [103]. The report showed that the PCE of DSSCs could be enhanced by the incorporation of GNRs with the focus on the fact that the increase for 0.005 % loading was up to 20% better than the control devices efficiency. This enhancement is largely the result of improved electron lifetime, the enhancement of dye loading, and the reduction of carrier recombination.

TiO₂/ZnO is an excellent composite for DSSCs for the application in heterogeneous photocatalysis owing to the superior properties of ZnO compared to TiO₂. Moreover, the non-toxic ZnO nanoparticles with superior properties such as fast carrier mobility could be prepared with facile methods for better absorption of dye [104, 105]. Similar to TiO₂, ZnO is a semiconductor oxide with good optical, mechanical and electrical properties [106]. Additionally, it has promising photo catalytic activity as well as antibacterial and antifouling effects [107]. It is worthwhile to note that the manufacturing cost of ZnO, is 75% less than that of Al₂O₃ and TiO₂ nanoparticles [108, 109].

ZnO/TiO₂ multipod nanostructures as the anodes of DSSC with

photoelectric conversion efficiency of 3.1% has been used by Cui et al. [110]. They were synthesized by hydrothermal technique using hetero-seed medium. The increase in the conversion efficiency can be the consequence of promising one-dimensional nanostructures that can accelerate electron transportation leading to the decrease in charge recombination. It has been shown by Zhong et al. [111], that the photoelectric conversion efficiency (PCE) for the electron transport layer of ZnO@TiO₂ nanorods in the form of core-shell structure is about 50 % higher than that of ZnO nanorod devices. This is because of following reasons; 1) the improved contact at the interface between perovskite layer and nanorods, 2) the inhibition of charge recombination. To enhance the power conversion efficiency of DSSCs based on TiO₂/ZnO Core/shell nanostructure, a scattering layer has been applied. The efficiency of TiO₂, ZnO, and TiO₂/ZnO nanostructures prepared via chemical methods is 1.76%, 1.65%, 2.41%, respectively whereas these quantities for ZnO / TiO₂ and TiO₂ /ZnO cells core/shell nanostructures coated without and with scattering layer are 4.1% and 5.89%, respectively [112]. Zhang et al. [113], prepared a heterostructured photoanode of titanium oxide nanorod arrays/zinc oxide nanosheets (TNRA/ZNSs) by a manageable chemical bath deposition technique for the use in quantum-dot-sensitized solar cells (QDSSCs) taking the advantages of nanosheets and nanorods. The report indicated that the prepared photoanode with slower electronic recombination rate and better specific surface area, has power conversion efficiency of 260% in comparison with the TNRA-based quantum dot solar cells

12. Conclusions and future insights

From the environmental point of view, solar cells have been the center of attention to be studied as a suitable electric power sources. Therefore, focal point of this review is based on different types of solar cells such as Si-based solar cells (amorphous Si solar cells, crystalline silicon solar cells and Monocrystalline silicon solar cells), Dye-Sensitized semiconductor, organic solar cells, tandem cells, DSSC, thin film solar cells, QDSC and PSC as well as TiO₂-based nanocomposites, with various functions in the solar cells. Significant improvement of PCE is required to provide the more competitive DSSCs technology. Furthermore, the production price and preparation of sustainable DSSCs should be mostly regarded. Targeted specific changes of every element (including counter electrode, organic dye and the photoanode) as a key factor cannot be forgotten. In this field, the paramount aim would be the exploration of the light harvesting, electron losses, electron-hole pairs recombination and the light harvesting, and hence improving the efficiency of solar cells.

Acknowledgments

The authors received no financial support for the research, authorship and/or publication of this article.

Conflict of Interest

All authors declare no conflicts of interest in this paper.

REFERENCES

- [1] A. Sánchez, E. Torres, R.d.A. Kalid, Renewable energy generation for the rural electrification of isolated communities in the Amazon Region, *Renewable and Sustainable Energy Reviews* 49 (2015) 278-290.
- [2] K.M.K. Yu, I. Curcic, J. Gabriel, S.C.E. Tsang, Recent advances in CO₂ capture and utilization, *ChemSusChem: Chemistry & Sustainability Energy & Materials* 1(11) (2008) 893-899.
- [3] B. Li, An Assessment of North Carolina's Future Electricity System Under Uncertainty, (2017).
- [4] D.P. Van Vuuren, A. Faber, Growing within limits A report to the Global Assembly 2009 of the Club of Rome, Netherlands, 2009, p. 128.
- [5] N.S. Lewis, G. Crabtree, A.J. Nozik, M.R. Wasielewski, P. Alivisatos, H. Kung, J. Tsao, E. Chandler, W. Walukiewicz, M. Spitler, Basic Research Needs for Solar Energy Utilization. Report of the Basic Energy Sciences Workshop on Solar Energy Utilization, April 18-21, 2005, DOE/SC (USDOE Office of Science (SC)), 2005.
- [6] S. Gardelis, A. Nassiopoulou, P. Manousiadis, N. Vouroutzis, N. Frangis, A silicon-wafer based pn junction solar cell by aluminum-induced recrystallization and doping, *Applied Physics Letters* 103(24) (2013) 241114.
- [7] W.-S. Jeong, J.-W. Lee, S. Jung, J.H. Yun, N.-G. Park, Evaluation of external quantum efficiency of a 12.35% tandem solar cell comprising dye-sensitized and CIGS solar cells, *Solar Energy Materials and Solar Cells* 95(12) (2011) 3419-3423.
- [8] G. Li, V. Shrotriya, J. Huang, Y. Yao, T. Moriarty, K. Emery, Y. Yang, High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends, *Nature Materials* 4(11) (2005) 864-868.
- [9] P.V. Kamat, Quantum dot solar cells. The next big thing in photovoltaics, *The journal of physical chemistry letters* 4(6) (2013) 908-918.
- [10] A. Goetzberger, J. Luther, G. Willeke, Solar cells: past, present, future, *Solar Energy Materials and Solar Cells* 74(1) (2002) 1-11.
- [11] D.M. Chapin, C. Fuller, G. Pearson, A new silicon p-n junction photocell for converting solar radiation into electrical power, *Journal of Applied Physics* 25(5) (1954) 676-677.
- [12] Z. Zhou, L. Yang, J. Gao, X. Chen, Structure-Relaxivity Relationships of Magnetic Nanoparticles for Magnetic Resonance Imaging, *Advanced Materials* 31(8) (2019) 1804567.
- [13] M.S.N. Shahrabak, F. Sharifianjazi, D. Rahban, A. Salimi, A Comparative Investigation on Bioactivity and Antibacterial Properties of Sol-Gel Derived 58S Bioactive Glass Substituted by Ag and Zn, *Silicon* 11(6) (2019) 2741-2751.
- [14] Z. Goudarzi, N. Parvin, F. Sharifianjazi, Formation of hydroxyapatite on surface of SiO₂-P₂O₅-CaO-SrO-ZnO bioactive glass synthesized through sol-gel route, *Ceramics International* 45(15) (2019) 19323-19330.
- [15] F. Sharifianjazi, N. Parvin, M. Tahriri, Formation of apatite nano-needles on novel gel derived SiO₂-P₂O₅-CaO-SrO-Ag₂O bioactive glasses, *Ceramics International* 43(17) (2017) 15214-15220.
- [16] M. Barekat, R.S. Razavi, F. Sharifianjazi, Synthesis and the Surface Resistivity of Carbon Black Pigment on Black Silicone Thermal Control Coating, Synthesis and Reactivity in Inorganic, Metal-Organic, and Nano-Metal Chemistry 45(4) (2015) 502-506.
- [17] S. Rahimi, F. Sharifianjazi, A. Esmailkhanian, M. Moradi, A.H. Safi Samghabadi, Effect of SiO₂ content on Y-TZP/Al₂O₃ ceramic-nanocomposite properties as potential dental applications, *Ceramics International* 46(8, Part A) (2020) 10910-10916.
- [18] E. Ghasali, M. Alizadeh, A.H. Pakseresh, T. Ebadzadeh, Preparation of silicon carbide/carbon fiber composites through high-temperature spark plasma sintering, *Journal of Asian Ceramic Societies* 5(4) (2017) 472-478.
- [19] A. Goetzberger, C. Hebling, Photovoltaic materials, past, present, future, *Solar energy materials and solar cells* 62(1-2) (2000) 1-19.
- [20] M. Imamzai, M. Aghaei, Y. Hanum Md Thayoob, M. Forouzanfar, A review on comparison between traditional silicon solar cells and thin-film CdTe solar cells, *Proceedings of National Graduate Conference (Nat-Grad, 2012, pp. 1-5.*
- [21] Types of Solar Panels, Grein Energy., (2015).
- [22] M.A. Maehlum, Energy informative the homeowner's guide to solar panels, best thin film solar panels—Amorphous, cadmium telluride or CIGS, Last updated 6 (2015).
- [23] J. Liu, Y. Yao, S. Xiao, X. Gu, Review of status developments of high-efficiency crystalline silicon solar cells, *Journal of Physics D: Applied Physics* 51(12) (2018) 123001.
- [24] Y. Zhuang, S. Zhong, Z. Huang, W. Shen, Versatile strategies for improving the performance of diamond wire sawn mc-Si solar cells, *Solar Energy Materials and Solar Cells* 153 (2016) 18-24.
- [25] Y. Zhang, J. Tao, Y. Chen, Z. Xiong, M. Zhong, Z. Feng, P. Yang, J. Chu, A large-volume manufacturing of multi-crystalline silicon solar cells with 18.8% efficiency incorporating practical advanced technologies, *RSC advances* 6(63) (2016) 58046-58054.
- [26] F. Cao, K. Chen, J. Zhang, X. Ye, J. Li, S. Zou, X. Su, Next-generation multi-crystalline silicon solar cells: Diamond-wire sawing, nano-texture and high efficiency, *Solar Energy Materials and Solar Cells* 141 (2015) 132-138.
- [27] J. Nelson, Imperial College Press, The physics of solar cells, Singapore, 2003.
- [28] M. Tao, Physics of Solar Cells, Terawatt Solar Photovoltaics, Springer2014, pp. 21-45.
- [29] W. Shen, Z. Li, Physics and Devices of Silicon Heterojunction Solar Cells, Beijing: Science Press, 2014.

- [30] S. Zhang, Study of fluorine-doped tin oxide (FTO) thin films for photovoltaics applications, Grenoble Alpes, 2017.
- [31] M.A. Green, J. Zhao, A. Wang, P.J. Reece, M. Gal, Efficient silicon light-emitting diodes, *Nature* 412(6849) (2001) 805-808.
- [32] C. Battaglia, A. Cuevas, S. De Wolf, High-efficiency crystalline silicon solar cells: status and perspectives, *Energy & Environmental Science* 9(5) (2016) 1552-1576.
- [33] B. Srinivas, S. Balaji, M. Nagendra Babu, Y. Reddy, Review on present and advance materials for solar cells, *International Journal of Engineering Re-search-Online* 3 (2015) 178-182.
- [34] P. Würfel, U. Würfel, *Physics of solar cells: from basic principles to advanced concepts*, John Wiley & Sons, USA, 2016.
- [35] S. Dimitrijević, *Principles of semiconductor devices*, Oxford university press New York, USA, 2012.
- [36] M. Bertolli, *Solar Cell Materials. Course: Solid State II*, Department of Physics, University of Tennessee, USA, 2008.
- [37] M.A. Green, Prospects for photovoltaic efficiency enhancement using low-di-mensional structures, *Nanotechnology* 11(4) (2000) 401-405.
- [38] R. Bergmann, Crystalline Si thin-film solar cells: a review, *Applied physics A* 69(2) (1999) 187-194.
- [39] L.C. Lew Yan Voon, L.R. Ram-Mohan, R.A. Soref, Electronic and optical properties of (001) Si/ZnS heterostructures, *Applied Physics Letters* 70(14) (1997) 1837-1839.
- [40] P. Yianoulis, R. Nelson, Effect of surface defects on the ionization energies of adsorbed dye molecules, *Photographic Sci. Eng* 18 (1974) 94-99.
- [41] P. Yianoulis, R.C. Nelson, Coulomb effect on the energy levels in molecular crystals, *Molecular Physics* 39(1) (1980) 261-269.
- [42] S. Zhang, Y. Qin, J. Zhu, J. Hou, Over 14% Efficiency in Polymer Solar Cells Enabled by a Chlorinated Polymer Donor, *Advanced Materials* 30(20) (2018) 1800868.
- [43] F. Gao, *Advanced Nanomaterials for Solar Cells and Light Emitting Diodes*, Elsevier Science, Netherlands, 2019.
- [44] J. You, L. Dou, K. Yoshimura, T. Kato, K. Ohya, T. Moriarty, K. Emery, C.-C. Chen, J. Gao, G. Li, A polymer tandem solar cell with 10.6% power conversion efficiency, *Nature communications* 4(1) (2013) 1-10.
- [45] M.A. Halim, Harnessing sun's energy with quantum dots based next generation solar cell, *Nanomaterials* 3(1) (2013) 22-47.
- [46] O.E. Semonin, J.M. Luther, S. Choi, H.-Y. Chen, J. Gao, A.J. Nozik, M.C. Beard, Peak external photocurrent quantum efficiency exceeding 100% via MEG in a quantum dot solar cell, *Science* 334(6062) (2011) 1530-1533.
- [47] E. Asadi, A. Fassadi Chimeh, S. Hosseini, S. Rahimi, B. Sarkhosh, L. Bazli, R. Bashiri, A.H. Vakili Tahmorsati, A review of clinical applications of graphene quantum dot-based composites, *Journal of Composites and Compounds* 1(1) (2019) 31-40.
- [48] V. Salimian Rizi, F. Sharifianjazi, H. Jafarikhrami, N. Parvin, L. Saei Fard, M. Irani, A. Esmaeilkhani, Sol-gel derived $\text{SnO}_2/\text{Ag}_2\text{O}$ ceramic nanocomposite for H_2 gas sensing applications, *Materials Research Express* 6(11) (2019) 1150g2.
- [49] X.-F. Shi, X.-Y. Xia, G.-W. Cui, N. Deng, Y.-Q. Zhao, L.-H. Zhuo, B. Tang, Multiple exciton generation application of PbS quantum dots in ZnO@PbS /graphene oxide for enhanced photocatalytic activity, *Applied Catalysis B: Environmental* 163 (2015) 123-128.
- [50] Q. Zhang, Z. Jin, F. Li, Z. Xia, Y. Yang, L. Xu, First application of CoO nanorods as efficient counter electrode for quantum dots-sensitized solar cells, *Solar Energy Materials and Solar Cells* (2019) 110307.
- [51] A. Badawi, W.O. Al-Gurashi, A.M. Al-Baradi, N. Al-Hosiny, Alloying cadmium cobalt sulfide quantum dots for solar cells applications, *Materials Science in Semiconductor Processing* 95 (2019) 1-6.
- [52] S. Das, I. Alam, J. Raiguru, B. Subramanyam, P. Mahanandia, A facile method to synthesize CZTS quantum dots for solar cell applications, *Physica E: Low-di-mensional Systems and Nanostructures* 105 (2019) 19-24.
- [53] N. Ahn, D.-Y. Son, I.-H. Jang, S.M. Kang, M. Choi, N.-G. Park, Highly reproducible perovskite solar cells with average efficiency of 18.3% and best efficiency of 19.7% fabricated via Lewis base adduct of lead (II) iodide, *Journal of the American Chemical Society* 137(27) (2015) 8696-8699.
- [54] T. Casey, An Article on Perovskites Will Power New Low-Cost & Highly Efficient Solar Cells, *Clean Technical* 3 (2015).
- [55] D. Shi, Y. Zeng, W. Shen, Perovskite/c-Si tandem solar cell with inverted nanopyramids: realizing high efficiency by controllable light trapping, *Scientific reports* 5 (2015) 16504.
- [56] M.H. Ann, J. Kim, M. Kim, G. Alosaimi, D. Kim, N.Y. Ha, J. Seidel, N. Park, J.S. Yun, J.H. Kim, Device design rules and operation principles of high-power perovskite solar cells for indoor applications, *Nano Energy* 68 (2020) 104321.
- [57] C. Pothiklang, K. Hongsih, P. Ruankham, Synthesis of Perovskite Film by Using Lead Nitrate as Precursor for Perovskite Solar Cell Applications, *Materials Today: Proceedings* 17 (2019) 1224-1230.
- [58] N. Mufti, I.K. Laila, A. Fuad, A. Taufiq, The Impact of Growth Temperature on Nanorod Morphology and Optical Properties for $\text{CH}_3\text{NH}_3\text{PbI}_3$ Perovskite Solar Cell Device Application, *Materials Today: Proceedings* 17 (2019) 1627-1636.
- [59] K.U. Thakur, R. Kisslinger, K. Shankar, One-Dimensional Electron Transport Layers for Perovskite Solar Cells, *Nanomaterials* 7(5) (2017).
- [60] Z. Hu, S. Dong, Q. Xue, R. Xu, H.-L. Yip, F. Huang, Y. Cao, In-situ synthesis of metal nanoparticle-polymer composites and their application as efficient interfacial materials for both polymer and planar heterojunction perovskite solar cells, *Organic Electronics* 27 (2015) 46-52.
- [61] Y. Liu, F. Lang, T. Dittrich, A. Steigert, C.-H. Fischer, T. Köhler, P. Plate, J. Rappich, M.C. Lux-Steiner, M. Schmid, Enhancement of photocurrent in an ultra-thin perovskite solar cell by Ag nanoparticles deposited at low temperature, *RSC Advances* 7(3) (2017) 1206-1214.
- [62] T. Hyeon, L. Manna, S.S. Wong, Sustainable nanotechnology, *Chemical Society Reviews* 44(16) (2015) 5755-5757.
- [63] S.B. Khan, *Nanomaterials for Environmental Applications and their Fascinating Attributes*, Bentham Science Publishers, Netherlands, 2018.
- [64] X. Chen, C. Li, M. Grätzel, R. Kostecki, S.S. Mao, Nanomaterials for renewable energy production and storage, *Chemical Society Reviews* 41(23) (2012) 7909-7937.
- [65] E.S. Shibu, A. Sonoda, Z. Tao, Q. Feng, A. Furube, S. Masuo, L. Wang, N. Tamai, M. Ishikawa, V. Biju, Energy materials: supramolecular nanoparticles for solar energy harvesting, *Nano Reviews* 4(1) (2013) 21079.
- [66] S. Suhaimi, M.M. Shahimin, Z. Alahmed, J. Chyský, A. Reshak, Materials for enhanced dye-sensitized solar cell performance: Electrochemical application, *Int. J. Electrochem. Sci* 10(4) (2015) 2859-2871.
- [67] L. Bazli, M. Siavashi, A. Shiravi, A review of carbon nanotube/ TiO_2 composite prepared via sol-gel method, *Journal of Composites and Compounds* 1(1) (2019) 1-9.
- [68] N.G. Park, M.G. Kang, K.M. Kim, K.S. Ryu, S.H. Chang, D.K. Kim, J. van de Lagemaat, K.D. Benkstein, A.J. Frank, Morphological and Photoelectrochemical Characterization of Core-Shell Nanoparticle Films for Dye-Sensitized Solar Cells: Zn-O Type Shell on SnO_2 and TiO_2 Cores, *Langmuir* 20(10) (2004) 4246-4253.
- [69] C. Longo, M.-A. De Paoli, Dye-sensitized solar cells: a successful combination of materials, *Journal of the Brazilian Chemical Society* 14 (2003) 898-901.
- [70] M. Shakeel Ahmad, A.K. Pandey, N. Abd Rahim, Advancements in the development of TiO_2 photoanodes and its fabrication methods for dye sensitized solar cell (DSSC) applications. A review, *Renewable and Sustainable Energy Reviews* 77 (2017) 89-108.
- [71] S. Chuangchote, T. Sagawa, S. Yoshikawa, Efficient dye-sensitized solar cells using electrospun TiO_2 nanofibers as a light harvesting layer, *Applied Physics Letters* 93(3) (2008) 033310.
- [72] N.A. Ilahi, R. Suryana, F. Nurrozyid, N.T. Linda Kusuma, Electrospinning Ti-tanium Dioxide (TiO_2) nanofiber for dye sensitized solar cells based on Bryophyta as a sensitizer, *Journal of Physics Conference Series (Online)* 795(1) (2017) 7.
- [73] J. Sun, X. Yang, L. Zhao, B. Dong, S. Wang, Ag-decorated TiO_2 nanofibers for highly efficient dye sensitized solar cell, *Materials Letters* 260 (2020) 126882.
- [74] J.V. Patil, S.S. Mali, A.P. Patil, P.S. Patil, C.K. Hong, Highly efficient mixed-halide mixed-cation perovskite solar cells based on rGO- TiO_2 composite nanofibers, *Energy* 189 (2019) 116396.
- [75] V.P. Dinesh, R. Sriram kumar, A. Sukhananazerin, J. Mary Sneha, P. Manoj Kumar, P. Biji, Novel stainless steel based, eco-friendly dye-sensitized solar cells using electrospun porous ZnO nanofibers, *Nano-Structures & Nano-Objects* 19 (2019) 100311.
- [76] M. Motlak, A.M. Hamza, M.G. Hamed, N.A.M. Barakat, Cd-doped TiO_2 nanofibers as effective working electrode for the dye sensitized solar cells, *Materials Letters* 246 (2019) 206-209.
- [77] Y.-H. Nien, H.-H. Chen, H.-H. Hsu, P.-Y. Kuo, J.-C. Chou, C.-H. Lai, G.-M. Hu, C.-H. Kuo, C.-C. Ko, Enhanced photovoltaic conversion efficiency in dye-sensitized solar cells based on photoanode consisting of $\text{TiO}_2/\text{GO}/\text{Ag}$ nanofibers, *Vacuum* 167 (2019) 47-53.
- [78] Y.-Y. Liu, X.-Y. Ye, Q.-Q. An, B.-X. Lei, W. Sun, Z.-F. Sun, A novel synthesis of the bottom-straight and top-bent dual TiO_2 nanowires for dye-sensitized solar cells, *Advanced Powder Technology* 29(6) (2018) 1455-1462.
- [79] S. Ni, D. Wang, F. Guo, S. Jiao, Y. Zhang, J. Wang, B. Wang, L. Yuan, L. Zhang, L. Zhao, Efficiency improvement of TiO_2 nanowire arrays based dye-sensitized solar cells through further enhancing the specific surface area, *Journal of Crystal Growth* 505 (2019) 62-68.

- [80] M.G.C.M. Kumari, C.S. Perera, B.S. Dassanayake, M.A.K.L. Dissanayake, G.K.R. Senadeera, Highly efficient plasmonic dye-sensitized solar cells with silver nanowires and TiO₂ nanofibres incorporated multi-layered photoanode, *Electrochimica Acta* 298 (2019) 330-338.
- [81] X. Liang, Y. Cheng, X. Xu, R. Dong, D. Li, Z. Zhou, R. Wei, G. Dong, S.-W. Tsang, J.C. Ho, Enhanced performance of perovskite solar cells based on vertical TiO₂ nanotube arrays with full filling of CH₃NH₃PbI₃, *Applied Surface Science* 451 (2018) 250-257.
- [82] C. Liu, T. Li, Y. Zhang, T. Kong, T. Zhuang, Y. Cui, M. Fang, W. Zhu, Z. Wu, C. Li, Silver nanoparticle modified TiO₂ nanotubes with enhanced the efficiency of dye-sensitized solar cells, *Microporous and Mesoporous Materials* 287 (2019) 228-233.
- [83] W.-Y. Rho, H.-S. Kim, W.-J. Chung, J.S. Suh, B.-H. Jun, Y.-B. Hahn, Enhancement of power conversion efficiency with TiO₂ nanoparticles/nanotubes-silver nanoparticles composites in dye-sensitized solar cells, *Applied Surface Science* 429 (2018) 23-28.
- [84] A.R. Jeyaraman, S.K. Balasingam, C. Lee, H. Lee, B. Balakrishnan, S. Manickam, M. Yi, H.-J. Kim, K. Sivalingam Nallathambi, Y. Jun, H. Kuzhandaivel, Enhanced solar to electrical energy conversion of titania nanoparticles and nano-tubes-based combined photoanodes for dye-sensitized solar cells, *Materials Letters* 243 (2019) 180-182.
- [85] M. Batmunkh, M.J. Biggs, J.G. Shapter, Carbon Nanotubes for Dye-Sensitized Solar Cells, *Small* 11(25) (2015) 2963-2989.
- [86] F.W. Low, C.W. Lai, Recent developments of graphene-TiO₂ composite nanomaterials as efficient photoelectrodes in dye-sensitized solar cells: A review, *Renewable and Sustainable Energy Reviews* 82 (2018) 103-125.
- [87] C.-C. Ting, W.-S. Chao, Efficiency improvement of the DSSCs by building the carbon black as bridge in photoelectrode, *Applied Energy* 87(8) (2010) 2500-2505.
- [88] H. Jaafar, Z.A. Ahmad, M.F. Ain, The use of carbon black-TiO₂ composite prepared using solid state method as counter electrode and E. conferta as sensitizer for dye-sensitized solar cell (DSSC) applications, *Optical Materials* 79 (2018) 366-371.
- [89] M.U. Rahman, F. Xie, X. Sun, M. Wei, Palladium nanoparticles on nitrogen doped acetylene carbon black as an efficient counter electrode for dye-sensitized solar cells, *Journal of Electroanalytical Chemistry* 848 (2019) 113317.
- [90] J. Nissfolk, K. Fredin, A. Hagfeldt, G. Boschloo, Recombination and Transport Processes in Dye-Sensitized Solar Cells Investigated under Working Conditions, *The Journal of Physical Chemistry B* 110(36) (2006) 17715-17718.
- [91] J. Cai, Z. Chen, J. Li, Y. Wang, D. Xiang, J. Zhang, H. Li, Enhanced conversion efficiency of dye-sensitized solar cells using a CNT-incorporated TiO₂ slurry-based photoanode, *AIP Advances* 5(2) (2015) 027118.
- [92] H. Peng, X. Sun, W. Weng, X. Fang, *Polymer Materials for Energy and Electronic Applications*, Elsevier Science, Netherlands, 2016.
- [93] J.K.W. Sandler, J.E. Kirk, I.A. Kinloch, M.S.P. Shaffer, A.H. Windle, Ultra-low electrical percolation threshold in carbon-nanotube-epoxy composites, *Polymer* 44(19) (2003) 5893-5899.
- [94] J.D. Roy-Mayhew, I.A. Aksay, Graphene Materials and Their Use in Dye-Sensitized Solar Cells, *Chemical Reviews* 114(12) (2014) 6323-6348.
- [95] T. Chen, W. Hu, J. Song, G.H. Guai, C.M. Li, Interface Functionalization of Photoelectrodes with Graphene for High Performance Dye-Sensitized Solar Cells, *Advanced Functional Materials* 22(24) (2012) 5245-5250.
- [96] Y.-B. Tang, C.-S. Lee, J. Xu, Z.-T. Liu, Z.-H. Chen, Z. He, Y.-L. Cao, G. Yuan, H. Song, L. Chen, L. Luo, H.-M. Cheng, W.-J. Zhang, I. Bello, S.-T. Lee, Incorporation of Graphenes in Nanostructured TiO₂ Films via Molecular Grafting for Dye-Sensitized Solar Cell Application, *ACS Nano* 4(6) (2010) 3482-3488.
- [97] H. Wang, Y.H. Hu, Graphene as a counter electrode material for dye-sensitized solar cells, *Energy & Environmental Science* 5(8) (2012) 8182-8188.
- [98] N. Yang, J. Zhai, D. Wang, Y. Chen, L. Jiang, Two-Dimensional Graphene Bridges Enhanced Photoinduced Charge Transport in Dye-Sensitized Solar Cells, *ACS Nano* 4(2) (2010) 887-894.
- [99] V.S. Manikandan, A.K. Palai, S. Mohanty, S.K. Nayak, Hydrothermally synthesized self-assembled multi-dimensional TiO₂/Graphene oxide composites with efficient charge transfer kinetics fabricated as novel photoanode for dye sensitized solar cell, *Journal of Alloys and Compounds* 793 (2019) 400-409.
- [100] A. Timoumi, S.N. Alamri, H. Alamri, The development of TiO₂-graphene oxide nano composite thin films for solar cells, *Results in Physics* 11 (2018) 46-51.
- [101] S.N. Sadikin, M.Y.A. Rahman, A.A. Umar, T.H.T. Aziz, Improvement of dye-sensitized solar cell performance by utilizing graphene-coated TiO₂ films photoanode, *Superlattices and Microstructures* 128 (2019) 92-98.
- [102] C. Jeganathan, T.C. Sabari Girisun, S. Vijaya, S. Anandan, Improved charge collection and photo conversion of bacteriorhodopsin sensitized solar cells coupled with reduced graphene oxide decorated one-dimensional TiO₂ nanorod hybrid photoanodes, *Electrochimica Acta* 319 (2019) 909-921.
- [103] R. Akilimali, G.S. Selopal, D. Benetti, I. Serrano-Esparza, P.A. Algara-bel, J.M. De Teresa, Z.M. Wang, B. Stansfield, H. Zhao, F. Rosei, Hybrid TiO₂-Graphene nanoribbon photoanodes to improve the photoconversion efficiency of dye sensitized solar cells, *Journal of Power Sources* 396 (2018) 566-573.
- [104] S.S. Kanmani, K. Ramachandran, Synthesis and characterization of TiO₂/ZnO core/shell nanomaterials for solar cell applications, *Renewable Energy* 43 (2012) 149-156.
- [105] S. Panigrahi, D. Basak, Core-shell TiO₂/ZnO nanorods for efficient ultra-violet photodetection, *Nanoscale* 3(5) (2011) 2336-2341.
- [106] E. Gharoy Ahangar, M.H. Abbaspour-Fard, N. Shahmahmasebi, M. Khojastehpour, P. Maddahi, Preparation and Characterization of PVA/ZnO Nanocomposite, *Journal of Food Processing and Preservation* 39(6) (2015) 1442-1451.
- [107] M. Al-Fori, S. Dobretsov, M.T.Z. Myint, J. Dutta, Antifouling properties of zinc oxide nanorod coatings, *Biofouling* 30(7) (2014) 871-882.
- [108] S. Liang, K. Xiao, Y. Mo, X. Huang, A novel ZnO nanoparticle blended poly-vinylidene fluoride membrane for anti-irreversible fouling, *Journal of Membrane Science* 394-395 (2012) 184-192.
- [109] I. Tajzad, E. Ghasali, Production methods of CNT-reinforced Al matrix composites: a review, *Journal of Composites and Compounds* 2(2) (2020) 1-9.
- [110] Y. Cui, W. Wang, N. Li, R. Ding, K. Hong, Hetero-seed mediated method to synthesize ZnO/TiO₂ multipod nanostructures with ultra-high yield for dye-sensitized solar cells, *Journal of Alloys and Compounds* 805 (2019) 868-872.
- [111] M. Zhong, L. Chai, Y. Wang, Core-shell structure of ZnO@TiO₂ nanorod arrays as electron transport layer for perovskite solar cell with enhanced efficiency and stability, *Applied Surface Science* 464 (2019) 301-310.
- [112] N. Rajamanickam, S.S. Kanmani, K. Jayakumar, K. Ramachandran, On the possibility of ferromagnetism and improved dye-sensitized solar cells efficiency in TiO₂/ZnO core/shell nanostructures, *Journal of Photochemistry and Photobiology A: Chemistry* 378 (2019) 192-200.
- [113] Y. Zhang, X. Zhong, D. Zhang, W. Duan, X. Li, S. Zheng, J. Wang, TiO₂ nanorod arrays/ZnO nanosheets heterostructured photoanode for quantum-dot-sensitized solar cells, *Solar Energy* 166 (2018) 371-378.