Contribution of Nanomaterials to the Development of Solar Cell Technology: A Review

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Solar cells are the future of renewable and sustainable energy. Many researchers, academicians, and PV industry experts are working on solar cells to improve their performance. Low cost and high conversion efficiency are the main challenges in making solar cells more competitive and a better alternative to traditional energy sources like fossil fuel. By improving the existing technologies of solar cells, nanotechnology is the key solution for both these challenges. Different nanostructured materials are used in solar cells in different ways to improve their performance. Nanostructured solar cells have several advantages. These benefits include: (1) maximizing the efficiency of a single junction solar cell by employing new concepts, (2) overcoming practical limitations in existing devices, such as modifying the properties of existing materials or implementing nanostructures to overcome lattice matching limitations, and (3) having the potential for low-cost solar cell structures by employing self-assembled nanostructures. During this study, solar cell technology with the help of nanomaterials has been studied in detail. The review says that the incident radiation is improved by a factor of nine and the collector efficiency is increased by 10 % more than conventional solar cells without the use of nanomaterials. This review article gives information about the contribution of nanomaterials to the development of solar cell technology, its limitations, and opportunities for further research.

Keywords: Solar cell, Nanomaterials, Photovoltaic effect.

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1. INTRODUCTION

The Sun is the primary source of abundant energy. A solar cell is a device that converts sunlight into electrical power. The fuel for the solar cell is sunlight which is free of cost and abundant. Solar cells can convert sunlight directly into electrical energy instead of some intermediate form [1]. The basic principle used to produce a voltage or current is called the photovoltaic effect [2]. Solar cells give high power to weight ratio compared to other power resources like batteries [1]. But the area occupied by the cell and the cost of the cell to produce electricity may be relatively large [2]. So, low cost and more conversion efficiency are the crucial tasks to make solar cell energy more competitive [1]. Researchers are trying to find a cost-effective method to use solar energy, giving more power conversion efficiency. The expensive silicon wafer is used in the conventional solar cell which is known as a first-generation solar cell. Researchers are trying to find some new materials that are cost-effective and will give more efficiency. Nanomaterials are the key solution to this. Normally, their properties and characteristics are depending on the size and shape of the materials. When their size changes to less than one hundred nanometers (nm) they are called nanomaterials. At this scale, their properties (electronics, optical, mechanical, chemical) are changed from their bulk scale. Due to this, these nanomaterials are used in solar cells. It also reduces the manufacturing cost compared to conventional silicon solar cells [3].

Therefore, in this review article by keeping in mind the efficient use of nanomaterials in the development of solar cells, we will study different nanomaterials and their contribution to the development of solar cells.

2. DIFFERENT GENERATIONS OF SOLAR CELLS AND THEIR COMPARISONS

2.1. First Generation Solar Cell

First-generation solar cells use a wafer crystalline silicon technique. This is the old and most popular technique because of its high efficiency [4, 5]. This technique is divided further into two groups: single/monocrystalline silicon solar cell and poly/multi-crystalline silicon solar cell [3]. If the wafer is made up of a single silicon crystal, it is called a single/monocrystal-line silicon solar cell [5]. If several different crystals (crystal grains) are used, coupled to one another in a single cell then it is called a multi-crystalline silicon solar cell [3, 5]. The recorded highest efficiency of single/monocrystalline silicon solar cells is 26.7 % measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008 or ASTM G-173-03 global) [1, 6].

2.2. Second-Generation Solar Cell

It is most commonly known as thin-film solar cells. Compared to first-generation solar cells thin-film solar cells are less expensive because the materials used in this type of cells are very less and less manufacturing process [7-9]. Thin-film solar cells use very thin absorbing layers around the thickness of 1 μm [3]. Crystalline solar cells are composed of *p-n* homojunction, but thin-film solar cells are made from *p-n* heterojunctions [8]. Second-generation solar cells have high absorption coefficients; only a 1 μm thick

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semiconductor can absorb 90 % of the solar spectrum [5]. Thin-film solar cells are classified into main three categories:

1. Amorphous silicon solar cell.
2. Cadmium Telluride (CdTe) solar cell
3. Copper Indium Gallium Di-Selenide (CIGS) solar cell [3, 9].

2.3. Third-Generation Solar Cell

A new generation of solar cells has evolved as a result of the high costs of first-generation solar cells, and even the toxicity and scarcity of materials for second-generation solar cells [4].

The third-generation solar panels differ significantly from the first and second generations in that their efficiency is not dependent on the *p-n* junction design. Different types of nanomaterials, polymers, and organic dyes are used to make the third generation of solar panels [1]. Researchers are currently developing new nanomaterials and techniques to improve the energy conversion efficiency of third-generation solar cells [1]. Solar cells of the third generation include nanocrystal-based solar cells, polymer-based solar cells, dye-sensitized solar cells, and concentrated solar cells [5]. Nanocrystal solar cells are also known as quantum dot solar cells. The size of quantum dots is within a few nanometers [3, 10]. Due to the polymer substrate, polymer solar cells (PSC) are generally flexible solar cells. A PSC is made of thin functional layers that are serially interconnected and coated on a polymer foil or ribbon [3]. In most DSSC-based solar cells, dye molecules are used to connect the different electrodes. A semiconductor electrode (*n*-type TiO_2 and *p*-type NiO), a dye sensitizer, a redox mediator, and a counter electrode comprise the DSSC device [3]. Using liquid electrolytes (I-/I-3 redox pair) in DSSCs, overall solar conversion efficiency of more than 12 % has been observed. However, using liquid electrolytes in DSSCs has a major drawbacks, including short-term stability due to organic solvent evaporation and leakage, difficulties in sealing the device, electrode corrosion, and poor solubility of inorganic salts like KI, NaI, and LiI [4].

3. CLASSIFICATIONS OF THIRD-GENERATION SOLAR CELLS

1. Dye-sensitized solar cell
2. Nanocrystal solar cell
3. Polymer solar cell
4. Concentrated solar cell

Table 1 – Comparison of three generations of solar cells

Generation	Different types	Upsides	Downsides	References
First-generation	Single/ Mono-crystalline silicon solar cell	High efficiency (14 %-17.5 %)	Performance is poor at high temperature. Very expensive compared to other generations.	[5] [11]
	Poly/Multi-crystalline silicon solar cell.	High efficiency (12 %-14 %)	Performance is poor at high temperature. Very expensive compared to other generations.	[3], [5], [11]
Second Generation (Thin-film solar cell)	a-Si	Performance is good at cool as well as high temperatures. Less expensive compared to the first generation.	Less Efficiency as compared to first generation (4 %-8 %). It requires a long installation time and large space.	[3]
	CdTe	Performance is good at cool as well as high temperatures. Less expensive compared to the first generation.	Less efficiency as compared to first generation (9 %-11 %). Toxic due to Cd.	[8]
	CIGS (copper indium gallium di-selenide)	Performance is good at cool as well as high temperatures. Less expensive compared to the first generation.	Less Efficiency as compared to first generation (10 %-12 %).	[9]
Third generation	Nano crystal-based solar cells	Very good thermal stability. Less expensive compared to the first generation. It requires a short installation time.	Less Efficiency as compared to first generation (7 %-8 %).	[10]
	Polymer-based solar cells	Less expensive compared to the first generation. It requires a short installation time and less space.	Less efficiency as compared to first generation (3 %-10 %). Performance is not good at high temperatures.	[5]
	Dye-sensitized solar cells	Less expensive compared to the first generation. It requires a short installation time.	Less efficiency as compared to first generation (up to 10 %). Performance is not good at high temperatures.	[1], [5]

	Concentrated solar cells	High efficiency (up to 40 %). Very high thermal stability. Less expensive compared to the first generation	It requires a large installation time and large space.	[5]

5. ABOUT NANOMATERIALS

Nanomaterials have captured a major area of research with the number of application domains [1]. Nanomaterials are defined as "a natural, incidental, or manufactured material containing articles in an unbound state, as an aggregate, or as an agglomerate, and where one or more external dimensions in the size range 1-100 nm are present for 50 % or more of the particles in the number size distribution." ("Implications of nanoparticles in the aquatic environment") The European Commission approved this concept on October 18, 2011. Nanomaterials (NMs) have risen to prominence in technological breakthroughs because of their tunable physical, chemical, and biological properties, as well as their superior performance over bulk counterparts [12]. Materials of nanoscale dimensions are currently referred to by the following scientific terminology [1, 12].

Nanoscale: refers to diameters between 1 and 100 nanometers.

Nanoscience: It is the study of materials at the nanoscale to understand their size and structural properties, compare the development of individual atoms and molecules, and understand bulk material differences.

Nanotechnology: It is the application of scientific knowledge to alter and control materials on a microscopic scale for a variety of industrial applications.

Nanomaterial: It is a material with nanoscale external or inner dimensions.

Nanoparticles are entities with all three external dimensions formed at the nanoscale.

Nanofiber is a nanomaterial with two identical dimensions at the nanoscale and a longer third dimension.

Nanocomposite: A multiphase material with at least one nanoscale phase is referred to as a nanocomposite.

The physical characteristics of materials with dimensions in micrometer in diameter are mostly the same as those of bulk materials. On the other hand, nanometer-sized materials have physical properties that are completely different from those of bulk materials. Because transformations from bulk form to atoms and/or molecules occur in this size range, the materials exhibit some incredible features. Some unique properties of nanomaterials are 1) large surface area to volume ratio, 2) quantum confinement effect [13].

Nanomaterials are divided into three major categories [12]:

1. *Based on materials:*
– Carbon-based nanomaterials
– Organic-Inorganic Hybrid nanomaterials
– Composite nanomaterials
2. *Based on dimension:*
– 0-dimensional
– 1-dimensional
– 2-dimensional
– 3-dimensional
3. *Based on origin:*
– Natural nanomaterials
– Synthetic nanomaterials

6. CONTRIBUTION OF NANOMATERIALS TO IMPROVE PERFORMANCE OF SOLAR CELLS

In response to the high production and installation costs of first-generation solar cells (1G) and the low performance of second-generation solar cells (2G), researchers developed third-generation solar cells (3G) [11]. Organic materials (polymers), nanotubes, silicon wires, organic dyes, conductive plastics, and other materials are used to manufacture this new generation of solar cells, and there is still an opportunity for improvement in terms of performance and cost [14]. Nanotechnology is a strong tool for a variety of applications in the solar system, including energy conversion, storage, and conservation [7]. Nanomaterials have the potential to help overcome present performance limits and increase solar energy collection and conversion [14].

7. SOME NANOMATERIALS USED IN SOLAR CELL

7.1. Carbon-Based Nanomaterials

Carbon nanostructures, such as nanodots, fullerenes, nanotubes, graphene, and carbon nanotubes, have novel and excellent optoelectronic, physical, thermal, and mechanical properties, as well as a large surface area, thermal conductivity, electron mobility, and mechanical strength, making them ideal for use in solar cells [15]. CNTs can be used to manufacture perovskite layers, hole transport layers, and replace metal electrodes. The use of CNTs to modify hole transport layers in photovoltaics and a CNT-based composite as counter electrodes has been suggested to improve photovoltaic efficiency [15].

7.2. Organic-Inorganic and Hybrid (OIH) Based Nanomaterials

Solar cells with organic compounds have lower PCEs and lower life expectancy than typical 1st and 2nd-generation solar cells. They are, however, excellent for a variety of special applications because of their low fabrication cost, flexibility, and lightweight [16]. OIH solar cells could combine the benefits of inorganic materials, such as stability, high carrier mobility, and a simple fabrication process, with the benefits of organics, such as improved light absorption over a wide range of wavelengths, adjustable molecular structures for energy band alignment, and solution processability [16]. Si is one of the most appealing elements for OIH solar cells and has been widely employed in solar cell modules. The PCEs of OIH solar cells with Si that exceeded 10 % have been reported in several articles [16]. ZnO has drawn a lot of interest for application in OIH solar cells because of its air stability, ease of synthesis, and high light transmission [16]. TiO_2 has been widely employed in photovoltaic research due to its excellent chemical stability, low cost, non-toxicity, strong photocatalytic activity, and high photoelectric conversion efficiency. Nanostructured TiO_2 has been used in dye-sensitized solar cells, heterojunction solar cells, photocatalysis, and a variety of other applications [16]. The transparency and sheet resistance of Ag nanowire mesh electrodes are low. They are a good fit for organic solar cells' flexible substrates. The photocurrent has increased by 19 %, according to the data [11].

7.3. Graphene-Based Nanomaterials

Due to its great transparency and conductivity and its use as electrodes in solar cells, graphene is a well-known 2D material that is widely employed in the fabrication of solar cells. Because of its ambipolar electrical transport, it may be utilized as both an anode and a cathode. Graphene is a 2D material. In which one side is nanoscale and the other two are constrained along an axis. Carbon in this form is allotropic. In photovoltaic cells, graphene can be employed as the active layer, electron acceptor, and interfacial layers due to its low coefficient of light absorption. It differs from most 3D materials in terms of physical and chemical properties. Graphene is also known as a semi-metal or a zero-gap semiconductor. When comparing Si with graphene, we can observe that Si has two times less electron mobility than Graphene, making it a superconductor with a direct bandgap that allows it to absorb more photons than indirect bandgap semi-conductors. Graphene's exceptional optical qualities can be employed as semitransparent electrodes in solar panels to connect two subshells. The ideal Graphene has a high electron mobility of 105 cm^2/s at ambient temperature (V·s). As a result of its remarkable mechanical and electrical qualities, as well as its configurable bandgap, graphene can be used to replace Si semiconductors [17].

7.4. TMD (Transition-Metal Dichalcogenides)

These are semiconductors with the type MX_2 where M is a transition metal and X is a chalcogen such as (S, Se, Te). A few of them are 2D materials with intriguing properties such as direct bandgap, high light absorption, novel electrochemical properties, strong light-matter interaction, and excellent semi-conducting properties. TMDCs are a promising substitute for platinum used as a counter electrode in DSSCs because they have a large (PCE) and can build solar cells that are both cost-effective and efficient [17].

7.5. Zero-Dimensional Materials

0D structures have been used in several PV applications and improvement strategies. The down-conversion of high-energy photons was one of the early applications of quantum dots [13]. Because of the quantum confinement effect, QDs have unique features such as size and shape-dependent optical properties and discrete electrical density of states. QDs are also appealing for usage in next-generation solar cells because of their low-cost manufacture based on the solution technique [10]. In comparison to conventional solar cells, quantum dot solar cells have low resistance [1]. To absorb each photon, quantum dots solar cells create more electrons than traditional solar cells. These nanoparticles are typically made of titanium oxide (TiO_2) and zinc oxide (ZnO) and range in size from 1 to 20 nm [7]. Quantum dots may alter their bandgap and absorb different wavelengths because of their variable diameters. The bandgap energy is inversely related to quantum dot size [7].

7.6. One-Dimensional Materials

1D materials stand out as promising candidates due to their geometric arrangement [7]. For photovoltaic applications, metal, metal oxide, carbonaceous material, and conducting polymer have all been produced into a 1D structure ranging from the nanowire, nanofiber, nanorod, and nanotube [7]. A 1D structure has various benefits, including efficient charge trans-mission and collecting, which improves solar performance [18]. 1D nanostructured solar cells often have better reflection reduction and absorption increase throughout a broad spectrum and a wide range of incidence angles, as well as higher carrier collecting efficiency and self-cleaning capability [2]. Because of their distinct electrical and electronic characteristics, wide electrochemical stability window, and large surface area, SWCNT assemblies are ideal for energy conversion devices [18]. Double-walled carbon nanotubes (SWCNTs) have also been used directly as energy conversion materials in thin-film solar cells, with nanotubes acting as both photogeneration sites and a charge carrier collection/transport layer. Nanofibers have recently grown a lot of interest in solar cells because of their higher charge-collection efficiency, which means faster electron transport and slower recombination. However, because NFs have a smaller surface area than nanoparticles, they are less effective at improving DSSC performance [19]. The 1D-configuration of TiO_2 NFs enhances charge transfer along straight channels while also increasing light-harvesting through light scattering [19].

7.7. Two-Dimensional Material

The atomically thin bodies and high flexibility of 2D materials make them the ideal alternative for integration with future-generation solar technology, with the scaling electrical characteristics with a high electrical trend in photovoltaics going toward thinner active materials [20]. Graphene, a 2D nanostructure with unique mechanical, optical, and electrical characteristics, is one of the most appealing materials for usage in various solar cell types. In solar cells, graphene, graphene derivatives such as graphene oxide (GO) and reduced graphene oxide, graphene hybrids, and graphene in its functionalized form have been used as the photoanode, counter electrode, acceptor, and transportation layers [17]. Graphene has high carrier mobility, high electrical conductivity (zero-bandgap semimetal), high mechanical strength (the strongest material ever measured), high optical transparency, wide light response range, high thermal conductivity, large specific surface area, low cost, robust chemical stability, tunable bandgap, and other properties that make it appealing for a variety of applications [20].

8. SUMMARY AND FUTURE OPPORTUNITIES

Nanotechnology has opened a slew of new possibilities in materials science and engineering for boosting performance in a variety of fields. The use of nanomaterials in solar cells, particularly third-generation solar cells, has a significant impact on the various components of solar devices. The third-generation solar cells have high efficiencies but also have stability problems. Still, it has a bright future to achieve high efficiency for commercial use. Dye-sensitized solar cells are having a bright future because of their increased inefficiency. so, the third-generation solar cells will meet the desires concerning power conversion efficiency, cost and life stability.

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Внесок наноматеріалів у розвиток технології сонячних елементів: огляд

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Сонячні елементи – це майбутнє відновлюваної та стійкої енергії. Багато дослідників, академічних працівників та експертів фотоелектричної промисловості працюють над сонячними елементами, щоб покращити їх продуктивність. Низька вартість та висока ефективність перетворення є основними проблемами у підвищенні конкурентоспроможності сонячних елементів та кращою альтернативою традиційним джерелам енергії, таким як викопне паливо. Удосконалюючи існуючі технології сонячних елементів, нанотехнології є ключовим рішенням обох цих проблем. Різні наноструктурні матеріали використовуються в сонячних елементах для покращення їх продуктивності. Наноструктуровані сонячні елементи мають ряд переваг. Ці переваги включають: (1) максимальну ефективність сонячного елементу з одним переходом шляхом застосування нових концепцій, (2) подолання практичних обмежень у відомих пристроях, такі як модифікація властивостей існуючих матеріалів або впровадження наноструктур для подолання обмежень узгодження решітки, і (3) можливість створення недорогих конструкцій сонячних елементів за рахунок використання самозібраних наноструктур. У ході дослідження була детально вивчена технологія сонячних елементів за допомогою наноматеріалів. В огляді зазначено, що падаюче випромінювання покращено в дев'ять разів, а ефективність колектора збільшена на 10 % більше, ніж у звичайних сонячних елементів без використання наноматеріалів. Дана оглядова стаття містить інформацію про внесок наноматеріалів у розвиток технології сонячних елементів, її обмеження та можливості для подальших досліджень.

Ключові слова: Сонячна батарея, Наноматеріали, Фотоелектричний ефект.