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The General Properties of Solar Cells Generations - Quantum Dot as Study Case

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A B S T R A C T

Quantum dot solar cells are an important class of solar cells of the third generation because of their optoelectronic characteristics suitable for photovoltaic response because of quantum confinement effect. Quantum dot structured materials are characterized by having a tunable bandgap as a result of a size change in addition to create an intermediate band. Thus, the quantum dots more thoroughly absorb the sun spectrum, and as a result, the solar cell's effectiveness is increased. Quantum dot solar cells' importance lies in increasing the efficiency through an increase in the generation of electron-hole pairs as a result of a single photon being absorbed, in other words several exciton generations. In this review, the generations of solar cells, the existing types and the materials used in each generation will be discussed, as a result of a single additionally to the qualities of quantum dot solar cells and the materials of this type.

1. Introduction

Since ancient times, the sun is considered as an important and essential source of energy on the surface of the earth, and the use of solar energy has evolved throughout the ages with the development of science and technology. It was developed and used to produce electric energy based on the principle of electronic radiative conversion using photovoltaic devices or solar cells [1]. Solar cells are the most important devices that were made to exploit solar energy, which are characterized by their ease of installation in their places of use, they have renewable, sustainable, clean energy. Their technologies are not complicated, which they can be developed and used to develop other technologies. Using solar cells has created a wide job opportunity, their material and environmental requirements are available significantly. It needed a large capital in the beginning, but it does not need raw materials due to its availability in nature, nor does it need continuous maintenance [2]. However, despite these advantages, it is still very expensive compared to traditional electric energy. That is why great scientific and technical efforts have been made all over the world. As many specialized research laboratories in this field seek to improve the efficiency of these devices in terms of energy transformation on the one hand, and to reduce their cost on the other hand [3]. It is important to remember that solar cells were first created for use in space, as they were also providing satellites with electrical energy based on photovoltaic conversion [4].

2. Various Solar Cell Generations

There are various generations of solar cells, classified according to the materials used and how they are manufactured, and they all convert light energy into electrical energy.

1. First Generation Solar Cell:

It primarily uses silicon wafers and typically displays an efficiency of 15% to 20%. These solar cell varieties are the most prevalent on the market and are typically found on residential houses roofs. The benefits of this photovoltaic cells are manufactured from semiconductors, which is the most common and used silicon material due to its worldwide availability. The key to solar cell technology is its high stability and optimal performance. It costs a lot of energy to produce, though, and is solid. It is still commercially dominant (85%) due to its efficiency and longevity compared to other cells. This generation includes a lot of species:

- **Monocrystalline silicon Type:**

The earliest solar cells are still the most widely used and efficient ones, they are created from thin silicon wafers. Because the cells are separated into strips of massive single crystals that have been grown meticulously under strict controls, these are known as monocrystalline solar cells. A panel is made up of several cells that have been put out in a grid and are typically a few inches wide. Regardless of the type or internal form of the crystal, it is distinguished by its smooth and homogeneous shape, as seen in figure (1) [5].

Figure (1) monocrystalline solar cell

These cells offer a high efficiency of up to 24.2% when compared to other cell types, meaning that more power can be generated from a certain region of the panel.

- In (2011), it has been designed and fabricated of 3-terminal tandem solar cell (Si-Si: Ge) to replace the standard Si solar cell to improve their performance and reduce costs [6].
- A study on the impact of the monocrystalline silicon solar cell's spectral response and quantum efficiency was conducted in 2015, where the results showed that the spectral response and quantum efficiency increased with wavelength [7].
- In 2017, the study was done about n-type HP mc silicon's front emitter with diffused boron and full-area passivating rear contact, which led to a high efficiency of 21.9%. [8].

- **Polycrystalline Silicon Type:**

Compared to monocrystalline silicon wafers, which are made from molds of a single silicon crystal, it is less expensive to produce. It can be known from the front view of the cell as shown in figure (2), if the necessity for strictly controlled growing conditions is not necessary. A number of intertwined silicon crystals grow together in this shape. In terms of cost per square foot, these panels are less expensive than monocrystalline panels, but their efficiency is down to 19.3%.

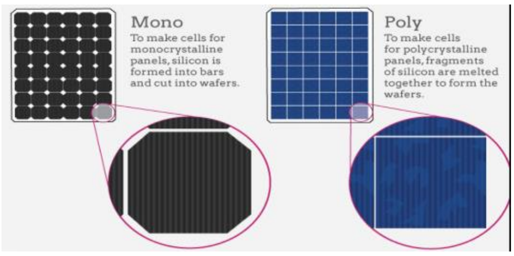

Figure (2) polycrystalline solar cell

- In 2015, the impact of temperature on photovoltaic characteristics was assessed. For poly-crystalline silicon, the maximum power decreased by (17%) as temperature increased from (15 to 60 ° C. With an increase in light intensity, the maximum current rose linearly [9].

- In (2017), Si-perovskite tandem solar cell used C-Si, $CH_3NH_3PbI_3$, and TiO_2, the highest efficiency performance ever reported was 27.29% [10].

2. <u>Solar Cell Of The Second Generation:</u>

Thin-film solar cells are what they are, which are characterized by having a thin thickness about (1 µm), that is their thickness is less than the silicon wafers used in the first generation by about (100 - 1000) times. It depends on amorphous silicon, copper indium gallium selenide and cadmium Telluride, with an efficiency of (10 – 15%). It has been avoided in the second generation of solar cells to use silicon wafers, and it was found that they have less consumption of materials, and this enables the production costs of this type of solar cell to be lower than those of the first generation. Additionally, it is possible to manufacture second-generation solar cells with some degree of flexibility. However, high-temperature treatments and discharge techniques are still used in the generation's solar cell production, in addition to this, it was discovered that the second generation is dependent on rare elements, and the price reflects this.

- **Amorphous Silicon Solar Cells Type:**

Silicon's poor absorption coefficient is its fundamental flaw. However, by adding hydrogen to highly amorphous silicon, it is possible to change the band gap from (1.1 ev) to (1.75 ev), mimicking CDTe, and the absorption coefficient increased to between (5 and 10) $cm^{(-1)}$. Si-H is a common abbreviation for this substance due to its high defect density. The efficiency rate is great, it was found. The best experimental solar cells have an efficiency of around 10%, whereas commercial solar cells have an efficiency of around 5%.

Figure (3) amorphous silicon solar cell

- **(Cadmium Telluride) CdTe solar cells:**

This type of solar cells has a high absorption capacity and it is easy to manufacture, especially the positive part of it, where the most widely used component for thin solar cells is cadmium telluride. In addition to other advantages, which is a broadband semiconductor, where the value of its absorption edge reaches to (2.4 ev), as a result, the majority of solar radiation passes through it. Figure (4) shows a typical CdTe solar cell, as it consists of p-type CdTe layer, n-type Cds layer and a thin layer of TCO that serves as a conductor and lets the incoming light pass through. This kind of solar cells' best efficiency is (16.5%- 20%).

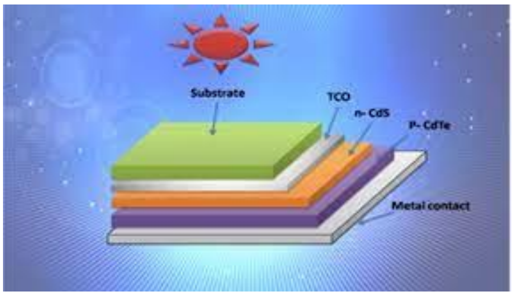

Figure (4) CdTe solar cell

- In 2015, employing CdSe heterojunction part photocurrent enhancement, a CdTe-based solar cell structure was created using soda-lime glass substrates covered with commercial SnO_2. This cell was found to be 15.2% efficient [11].

- In comparison to the similar devices without the ZnO buffer layer, the performance of CdZnS solar cells with a ZnO buffer layer that is transparent in 2019 has seen a conversion efficiency boost of up to 1.8% [12].

- **(Copper Indium Gallium Selenide) CIGS Solar Cells:**

CuInSe2 / Cds system, a photoelectric light detector, was invented in 1974. These materials were used in the construction of a solar cell in 1975, which demonstrated strength in comparison to silicon solar cells at the time. When compared to polycrystalline silicon solar cells in 2000, the efficiency of thin film CIGS solar cells was 19.9%. CuInSe2's band gap is quite close to the ideal value, although it has an approximately 100-fold higher absorption coefficient than silicon. Figure (5) shows the fundamental design of a CIGS solar cell [5].

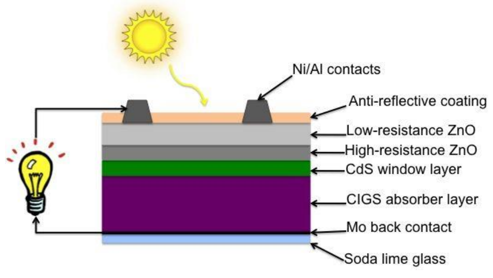

Figure (5) CIGS solar cell

Similar to Cdt solar cells, a small part of this semiconductor is used in the form of a negative semiconductor to form the double junction, additionally, because to the minimal amount of cadmium used here, between two glass panels and is situated, the environmental impact is middling. A wet technique can be used to create the CIGS solar cell, without need a vacuum. Consequently, the cost of manufacturing can be inexpensive. CIGS solar cells also have the benefit of allowing interconnections to be created on the same structure, like an integrated circuit, a single high-voltage cell as a result, say 12 volts, eliminating the requirement for external connections.

- In 2015, a power-conversion efficiency of (25.11%) was reached by using Silvaco-Atlas to simulate the performance of a double junction CGS/CIGS tandem solar cell with the CGS acting as the top-cell and the GIGS acting as the bottom-cell [13].

- With a notable increase in cell efficiency of about (19%), in 2020, band-gap grading and an array of Au plasmonic nanoparticles were used to assess the high performance of the ultra-thin CIGS solar cell [14].

3. Third generation solar cell

It is known as the generation of nanotechnology, and it is still in the stage of research, evaluation and development at the experimental laboratory levels. It is anticipated that they would use a variety of organic components, such as tiny molecules or pigment, and exhibit a wide range of creativity. As a result, dye solar cells are an organic solar cell's subclass. Additionally, the third generation includes prototype solar cells, costly and high-execution solar cells that set a world record for efficiency. Due to its high production cost, this type only has a minimally commercial applicability. Current research on a new class of thin-film solar cells shows that solar can achieve record efficiencies of over 20% in a very small area. In contrast, dye photovoltaic cells and organic solar cells provide a number of benefits, including mass production, quickness, affordability, and the use of potentially cheap and widely accessible ingredients. Similar to printing newspapers, known industrial (R2R) technology can be used to produce polymer solar cells. Silicon solar cells achieved the highest energy conversion efficiency, reaching 29%. Even though this technique is established and trustworthy, by boosting productivity and lowering manufacturing costs, the globe is starting to create new technology. Third-generation solar cells have a lot of potential and are currently being marketed, despite the fact that their performance and stability are still limited when compared to first- and second-generation solar cells. Recently, there has been a noticeable increase in research interest in polymeric solar cells [5]. This generation includes a lot of types:

- Organic solar cells.
- Dye-sensitized solar cells.
- Tandem or stacked multilayers.
- Quantum dots solar cells.

3.1 Solar Cell Industry Based On (III–V Group) Technique

At the beginning of the twentieth century, it was believed that the devices based on nanoelectronics would enable the manufacture of more solar cells, in addition to that it would have a great impact in meeting global energy requirements. But the question that imposes itself now is how is nanotechnology used in the production of solar energy. By incorporating nanoparticles into silicon panels via a thin layer of solar cells, nanotechnology is used in the field of solar energy, utilizing cylinders with no walls. Nano tubes, it is (silver fullerenes, cadmium telluride, and titanium dioxide). This will improve the capacity of solar panels to absorb various light wavelengths, and this is what distinguishes them from other regular solar panels. In other words, slices of cutting-edge nanomaterials are used to create solar cell panels that use nanotechnology, and grafted with points that work with quantum physics techniques and are called quantum dots (QD). It is anticipated that the amount of electricity generated by solar cells would rise, and these points are tiny materials that come from lead, selenium and cadmium, meaning that the diameter of the points does not exceed parts of a billionth of a meter [15].

In 2003, solar cells containing three InGaP, InGaAs, and Ge connections were produced using Ge substrates. This advancement in lattice matching and the DH tunnel for AlGaAs/InGaP structure junction with AlInP barriers led to a novel registration efficiency at AM1.5 (1-sun) of 31.7%. In addition, three-junction InGaP/GaAs/InGaAs cells with a record efficiency of 33.3% were developed [16].

- The efficiency of a metamorphic three-junction GaInP/GaInAs/Ge cell was measured and independently verified in 2007 at (240 suns) under the standard spectrum for terrestrial concentrator solar cells [17].
- A multi-junction cell that can absorb visible and IR wavelengths was proposed in 2011. The bottom unit of the proposed structural cell, which consists of two sub-cells, is a 20-period GaAs-Ge super lattice housed in a GaAs/Ge bulk solar cell. The AlAs/AlGaAs/GaAs cell, appropriate for short wavelengths, is proposed at the top of this cell. Through a typical tunnel junction that connects both components in series, collection efficiency is expected to reach the existing cutoff point of 42% (under one sun circumstances) [18].
- In (2013), an efficiency of more than (37%) have been evaluated for an InGaP/GaAs/InGaAs inverted triple-junction solar cells have been developed for a concentrator application [19].
- In 2016, the PIN junction structure of InGaAsN (Sb) was created to increase the effectiveness of the power conversion germanium-based (4-Junction) solar cell. Drift-diffusion simulations were used to model the subcell's performance.
- In (2018), the TCAD SILVACO gadget is used to create and implement multi-junction solar cells.. The results acquired are compared and evaluated for InGaP/GaAs/Ge and TJ solar cells made of InGaP/GaAs/InGaAs. The suggested InGaP/GaAs/InGaAs solar cell has an efficiency of 42.01%, compared to the optimized InGaP/GaAs/Ge TJ solar cell's efficiency of 39.61% [21].
- In (2019), a numerical analysis of the photovoltaic behavior of single-junction solar cells made of p-InGaN and n-InGaN is reported. The SCAPS (Solar Cell Capacity Simulator) software was used to simulate this solar cell. The optimal conversion efficiency of (15.32%), which corresponds to (64%) of the indium compositions, was validated at a band-gap of (1.32 eV) [22].

3.1.1 QUANTUM DOTS SOLAR CELLS

Quantum dot semiconductors have excellent optoelectronic properties such as changeable bandgap, multiple exciton generation (MEG), and high extinction coefficient. Because of this, due to their potential to produce solar cells that are very efficient, these materials have received a lot of interest. Quantum dot solar cells really have a conversion efficiency of 16.6%, which is the most efficiency possible, as opposed to the theoretical value of roughly 66%. To handling the difference between the actual and theoretical energy conversion efficiencies, strategies have been proposed to understand the relationship between the element composition properties, synthesis methods and physical structures [23].

3.1.1.1 QUANTUM DOTS PROPERTIES

in 1980, Alexei Ekimov and Alexander Efros discovered Quantum dots which became important [24], because of the quantum confinement effect which it derives its properties. It is considered a semiconductor that can be confined in 3-dimensions and its diameters range from (1-100) nm.

The properties of quantum dots are dependent on size of the nanocrystals. The quantum confinement effect is the change in the bandgap's size in backward proportional to how big quantum dots are. One of the most significant elements affecting the effectiveness of solar cells is the process of absorbing high-energy photons, because the substance is transparent to photons with energies below the band gap, but the photons whose energy is the same as or greater than the bandgap will be absorbed, producing an electron-hole pair that needs to be separated. In bulk semiconductors, when high-energy photons are absorbed, they will generate high-energy charge carries, which are called hot carriers. When it returns to its steady stable (relaxation) it will cause efficiency losses via what is called heat release [25].

In quantum dots, the capture of a single high-energy photon will generate multiple charge carriers (multiple excitation generation) because it suppresses the development of heat carriers, and thus the thermal losses in efficiency will decrease and the efficiency of solar cell will increase [26].

3.1.1.2 QUANTUM DOT MATERIALS

A different material can be used to manufacture quantum dots, but the selection of a semiconductor must take into account the absorption range of photon energy, in addition to other important properties.

The energy of photons in solar radiation ranges between (0.5 ev and 4 ev). The energy of sunlight corresponds to infrared radiation by 49%, 46% with the energy of visible light, and only 5% with ultraviolet radiation. The band gap of quantum dots must be within the energy range corresponding to infrared radiation to obtain high conversion efficiency.

In addition, MEG is an important factor in the quantum semiconductor of solar cells. It also requires a higher cooling time for the exciting to separate the charge carriers and extract them before recombining them [27]. Finally, to ensure optimal long-term performance, quantum materials must be extremely stable.

Table 1. semiconductor resources used usually in quantum dot for solar cells. "source: ahamad et al". [28]

Semiconductor	Excitation Bohr Radius (nm)	Bandgap Energy (eV)
PbS	40.0	0.41
GaAs	28.0	1.43
CdTe	15.0	1.50
CdSe	10.6	1.74
ZnSe	8.4	2.58
CdS	5.6	2.53

4. QUANTUM DOT SYNTHESIS

Numerous composition techniques have been created in an effort to produce high-quality components at the lowest feasible cost, with the least amount of environmental damage, and with the least amount of technological needs.
The variety of these techniques, as well as temperature and pressure, are controlled by the materials utilized in the production of quantum dots. These techniques could be chemical or physical. Quantum dots may be produced on a big scale and at a lower cost using chemical processes. The quality of the quantum dots, film thickness, and homogeneity are controlled using physical techniques. They are usually more expensive, but due to the high quality of the particles, they have become a good choice for researchers. One of the most common physical methods is Stransky-Krastanov, or SK method [29], where this method is used to fabricate quantum dots of high quality with molecular beam epitaxy technique. In the past decade, chemical methods have been developed whereby colloidal solutions are used to synthesize quantum dots. For better control the particle size, synthesis protocols have been used, as well as passivation techniques have been used to control surface defects. Temperature, pressure, reaction duration, and reactant concentrations are synthesis parameters that can change quantum dot characteristics and defect density. The most well-known techniques in quantum dot fabrication are consecutive ionic layer absorption, chemical bath deposition, and seller interaction. In order to enhance optoelectronic quantum dots' characteristics, it is necessary to reduce defects on their surfaces.

5. QUANTUM DOT SOLAR CELLS DESIGN

The requirements for reducing electricity generation costs by photovoltaic devices are to explore new materials and to design new devices to achieve remarkable progress.

Structures of solar cells affect the materials employed, technology requirements and manufacturing costs. The following are types of quantum dot solar cells:

1. Schottky solar cells based on metal / semiconductor junctions

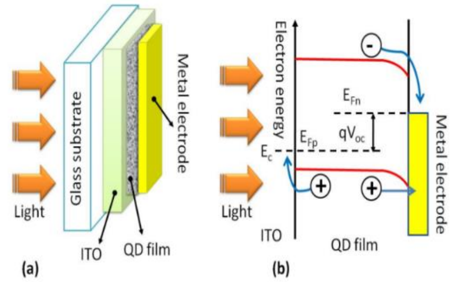

Figure (6) a) Schematic of Schottky barrier quantum dots based solar cell.
b) Band diagram of Schottky solar cell.

2. Heterojunction solar cells

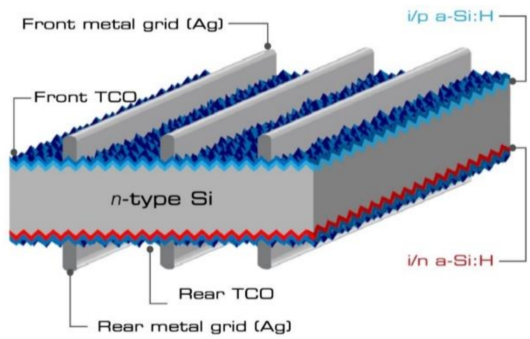

Figure (7) Schematic of heterojunction solar cell.

3. Quantum dot sensitized solar cells

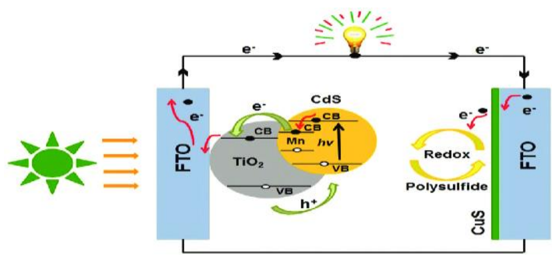

Figure (7) Schematic of Quantum Dot sensitized solar cell

In (2011), a quantum dot sensitized solar cell was used, where the CuInS2 material was used as a quantum dot layer with a thickness of (3.5 nm), a surface layer of TiO2, a CDs layer as a coating and the last layer of ZnS for passivation. Through the results, the efficiency of conversion reached about 4.2% [30].
In (2014), a standard GaAs solar cell and 40-layers of InAs/GaAs p-i-n QD were modeled and simulated using Silvaco TCAD and compared with experimental data for fabricated solar cells, where the conversion efficiency increased from 14.1% to 18.6% due to the use of QD [31].
GaAs p-i-n was structured and 40 – layers of GaSb QD were inserted inside the i – region and compared with the results of standard GaAs solar cell. It was noticed that the conversion efficiency increased from 16.48% to 22.4% (a relative increase of about 36.3%) in 2015 [32].
ITO/TiO2/P3HT&PCBM/Ag and ITO / TiO2 / CDs / P3HT & PCBM/Ag were structured and simulated using SILVACO TCAD in 2016. The simulation results of the fabricated solar cell, where the efficiency of this cell reached 1.8%, as it was close to the experimental results. This means that when CDS QD is inserted, the light absorption will increase, and thus the efficiency will improve [33].
In 2017, InAs QD material was inserted into the i region of GaAs solar cell (p-i-n) hetero-structure, and thus an increase in efficiency was obtained by 3.885%, and an increase in FF from 83.27% to 88.0538% [34].
In 2019, The realization of InAs/GaAs solar cell was studied in case of Quantum Well and Quantum Dots. InAs/GaAs QW was simulated using MATLAB software, as the efficiency of this cell reached 18.52%, compared to the standard solar cell, where the efficiency was 16.78%. For InAs/GaAs QD solar cell, it was simulated using SILVACO TCAD, where the efficiency in the ideal case reached 43.05%, while in the practical case the efficiency of this cell reached 9.1%, taking into account the presence of the valence band tail and discrete electron and by improving the number of Quantum Dots layers and doping it is possible to improve the efficiency of the solar cell to 11.29% [35]. In 2020, the effect of the performance of InGaAs/GaAs-based quantum dot intermediate band solar cells (QDIBSCs) were studied with the cap and passivation layers. AlGaAs was used as a cap layer and Si3N4 was used as a passivation layer. The results showed that the use of these layers improved the efficiency of the solar cell, as it changed from 21.6% to 27.8%. As the rate of recombination was decreased when using the cap layer and the reflection decreased by improving the rate of photovoltaic generation of the cell by using the passivation layer, thus increasing the efficiency [36].

Table 2. Comparison between solar cell generations

Generations	First generation	Second generation	Third generation
Efficiency %	10 - 15 %	15 - 20 %	Exceeding 20%
Types of each generation	Monocrystalline silicon type Polycrystalline silicon type	Amorphous silicon type CdTe type CIGS type	Organic solar cell Dye-sensities solar cell Tandem multilayers Quantum Dots solar cell

Conclusions

Quantum Dots have amazing light-absorbing properties, but even so, their computational potential makes them very far from photovoltaic devices. Quantum Dots Solar cells are substantially more powerful conversion efficiency than conventional solar cells. However, it still needs to be developed in terms of bandgap absorbers as well as multiple exciton generation (MEG). MEG is considered a very promising and effective feature in $QDSC_s$. In general, QD_s still needs to be developed to suit the slow carrier dynamics and its longer life

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