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QUANTUM DOTS ON SOLAR CELL

Sri Ramu D S[1], Rishi Nagendra[2]

Asst Professor, Dept Of Ece, SJCIT, Chickballapur, India[1]

UG Student, Dept Of Ece, SJCIT, Chickballapur, India[2]

Abstract- A cutting-edge new technology called quantum dot solar cells has the potential to completely transform the solar energy industry. These solar cells absorb sunlight and transform it into electricity using microscopic semiconductor particles called quantum dots. Due to their special optical and electronic characteristics, quantum dots are incredibly effective at converting solar energy into electrical energy. They can be tuned to absorb specific light wavelengths, making it possible to use the solar spectrum more effectively.

The efficiency of quantum dot solar cells has significantly improved in recent years, with some research teams reporting efficiencies of over 12%. Quantum dot solar cells are also a viable alternative for large-scale deployment because they may be produced at a lower cost than conventional silicon-based solar cells. The development of quantum dot solar cells still faces obstacles, such as enhancing their stability and endurance over time, despite these encouraging developments. But given its potential advantages, this technology represents a promising direction for further study and development in the area of renewable energy.

I. INTRODUCTION

Quantum dots are semiconductor nanoparticles, and quantum dots solar cells (QDSCs) are a relatively new type of solar cell technology that use them as the light-absorbing substance. This technology has the potential for high efficiency and low cost, making it a promising replacement for conventional silicon-based solar cells. The unique characteristics of quantum dots, which are nanoscale particles, include a size-tunable bandgap, a high surface-to-volume ratio, and effective charge carrier generation and transport. Due to their ability to absorb a wider range of solar energy's wavelengths and more effectively convert it into electrical energy than conventional materials, they are appealing candidates for use in solar cells.

Although research on QDSCs is still in its early stages, researchers have already achieved high power conversion efficiencies of over 12%, and further development could lead to even higher efficiencies. Quantum dots are a desirable option for the mass production of solar cells due to their low production costs, which may lower the price of solar energy. The advancement of QDSCs still faces obstacles, such as enhancing their long-term stability and toughness and cutting back on the toxic materials used in manufacturing them. However, the advantages of this technology could make it a fascinating area for further study and advancement in the field of renewable energy.It has taken more than 20 years of research to develop quantum dot (QD)-based solar cells, with the goal of outperforming single junction solar cells through increased efficiency. A single junction solar cell's efficiency has not yet been surpassed by any other device that is currently in use.

The only eco-friendly options that can satisfy the rising energy demands are solar and wind energy, which use no fuel. PV will replace wind energy due to its inherent advantages and eventually overtake it to become the main method of generating electricity. PV generates electricity at the world's lowest cost without any subsidies. The solar farm's 1.177 gigawatt of power, $872 million in capital expenditures, 7.8 square kilometres of land area, and 2.42 cents per kWh in customer costs are all given. As a result of these numbers, $0.74 per watt can be calculated as the installed PV system cost.

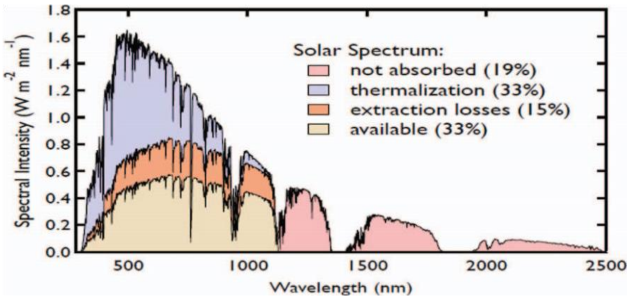

Fig. 1. Spectral Analysis of the losses for a bulk Si-based solar cell.

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With the aim of developing high efficiency solar cells that surpass the efficiency of single junction solar cells, research on nanomaterials and nanoscale heterostructures like QD (Fig. 2) has been going on for more than two decades.

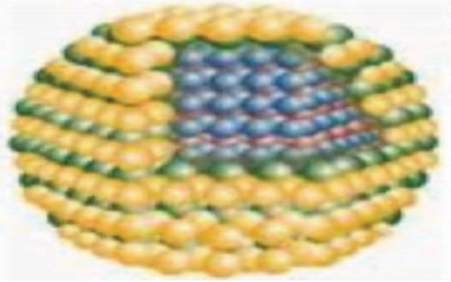

Fig. 2. Quantum dot

Even though QD-based solar cells' efficiency has increased from a meagre 5% in 2010 to almost 11% at the moment, single junction solar cells' efficiency (26.3%) still outpaces them by a wide margin.

Quantum confinement effects give semiconductor quantum dots (QDs), which are nanometer-sized, their distinctive optical and electronic characteristics. These QDs can lower production costs and help improve energy conversion efficiency when used in solar cells.

In contrast to the traditional silicon material used in solar cells, quantum dots (QDs) are used as the absorbing layer in quantum dots solar cells (QDSCs). The benefit of QDSCs is their capacity to absorb a wider range of solar spectrum, including both visible and infrared light, and transform it into electricity. This is because the QDs can be designed to absorb particular light wavelengths thanks to their special size-tunable optical properties.

Usually made from substances like cadmium selenide (CdSe), lead sulphide (PbS), or lead selenide, QDs are used in QDSCs (PbSe). Due to the high absorption coefficients of these substances, light can be effectively absorbed and converted into electricity. Furthermore, QDs are an appealing option for large-scale production because they can be made using inexpensive solution-based methods.

The limited stability of the QDs, especially when exposed to air and moisture, is one of the difficulties with QDSCs. By creating new, more stable QD materials and developing encapsulation methods to shield the QDs from deterioration, researchers are attempting to address this problem.

II. NANOSTRUCTURE FUNDAMENTALS

Nanostructure fundamentals play a crucial role in the performance of quantum dots solar cells (QDSCs). The design and engineering of nanostructures in QDSCs can significantly impact their efficiency, stability, and optoelectronic properties. Here are some key nanostructure fundamentals in QDSCs:

1.Quantum confinement: Quantum dots are nanoscale structures that exhibit quantum confinement effects, which arise due to the restriction of electron motion in all three dimensions. The size of the quantum dots determines their bandgap, which in turn affects their optical properties, such as absorption and emission spectra. By controlling the size of the quantum dots, their energy levels can be tuned to match the solar spectrum, enabling efficient absorption and utilization of sunlight in QDSCs.

2.Surface passivation: The surface of quantum dots is highly reactive and can lead to surface traps or states that can reduce the overall efficiency of QDSCs. Surface passivation techniques involve coating the quantum dots with a thin layer of material to protect them from surface-related defects and improve their stability and performance. Surface passivation can be achieved using various methods, such as using ligands, organic or inorganic shell layers, or surface treatments, to minimize surface recombination and enhance charge carrier transport.

3.Heterostructures:Nanostructured heterostructures, which are interfaces between different materials, are commonly used in QDSCs to improve their performance. Heterostructures can be designed to facilitate efficient charge separation and transport, as well as enhance light absorption. For example, core/shell heterostructures, where a quantum dot core is coated with a shell of a different material, can help improve the stability of the quantum dots, enhance light absorption, and facilitate charge transfer across the interface.

4.Charge transport pathways: Efficient charge transport is critical in QDSCs to ensure that photo-generated charges (electrons and holes) can move effectively through the device and be collected at the respective electrodes. Nanostructures, such as mesoporous films, nanowires, or nanocomposites, can be used to create well-defined charge transport pathways, reduce charge recombination losses, and improve overall charge collection efficiency.

5.Electrode materials: The choice of electrode materials in QDSCs can also impact their performance. Nanostructured electrodes, such as transparent conductive oxide (TCO) thin films or nanostructured metal electrodes, can provide large surface areas for charge collection, improve electron transport, and reduce series resistance losses.

6.Nanostructured back reflectors: Nanostructured back reflectors can enhance light trapping in QDSCs, increasing the optical path length and hence improving the absorption of light. Nanostructured back reflectors can be designed using various approaches, such as nanoparticle arrays, nanowire arrays, or textured surfaces, to scatter or trap light and increase the absorption of incident photons.

These are some of the essential principles of nanostructure used in quantum dot solar cells. Research is ongoing to improve the performance, stability, and affordability of QDSC nanostructures in order to use them in real-world solar energy conversion applications. The properties of these materials could be used to improve the efficiency of solar energy conversion if they can be successfully manufactured.

There are four different types of nanostructures that can be categorised: one-dimensional (1D), two-dimensional (2D), three-dimensional (3D), and zero-dimensional (0D). Only one dimension—the largest of the three—exists in 1D nanostructures, compared to the other two. Polymers are a type of one-dimensional structure. The two dimensions of 2D nanostructures are significantly larger than the third dimension. Thin films are an example of a 2D structure. The aggregation of nanoparticles creates 3D nanostructures, which resemble honeycombs or matrices. A nanometer is the width of all 0D structures.
Consider a zero-dimensional structure with dimensions that are only a few nanometers apart; the density of states in this structure will be quantized in all three dimensions. Think about a two-dimensional structure where only one dimension is in the nanoscale range; the density of states in this structure will only be quantized in that one dimension.

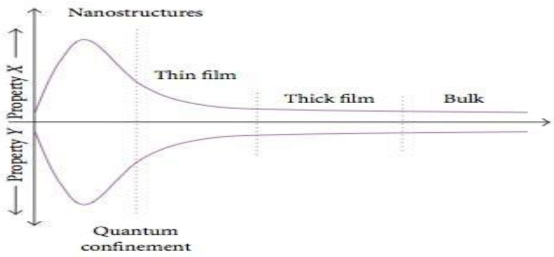

Fig. 3. Change of properties of a material with dimension

In an isolated nanostructure, researchers have been able to make use of these intriguing properties, but they haven't had much luck doing so in a device made from the same nanostructures.

III. PROCESSING OF NANOSTRUCTURES

The processing of nanostructures in quantum dots solar cells (QDSCs) involves the fabrication and integration of nanostructured materials to create high-performance solar cell devices. Here are some key processing steps involved in the fabrication of nanostructured QDSCs:

1.Synthesis of quantum dots: The first step in the processing of QDSCs is the synthesis of quantum dots, which are typically prepared using solution-phase methods such as colloidal chemistry, hot injection, or sol-gel processes. The synthesis of quantum dots involves controlling the size, shape, and composition of the dots to optimize their optical and electronic properties for solar cell applications.

2.Surface modification of quantum dots: The surface of quantum dots is highly reactive and can lead to surface-related defects that can reduce the performance and stability of QDSCs. Surface modification techniques, such as ligand exchange, can be used to passivate the surface of quantum dots and improve their stability and performance.

3.Deposition of quantum dots: Quantum dots are typically deposited onto a substrate to form the active layer of the solar cell. Deposition methods can include spin-coating, drop-casting, or layer-by-layer assembly. The deposition process is critical for controlling the morphology, thickness, and uniformity of the quantum dot layer, which can impact the performance of the device.

4.Formation of heterostructures: Nanostructured heterostructures, which are interfaces between different materials, can be designed to improve the performance of QDSCs. Heterostructures can be created by depositing different layers of materials, such as a core-shell structure, onto the surface of quantum dots. The formation of heterostructures can enhance the charge separation and transport properties of QDSCs.

5.Device fabrication: The active layer of quantum dots is integrated into a device structure to form a complete QDSC. The device structure typically includes a substrate, a transparent conductive oxide (TCO) layer, a hole transport material (HTM) layer, and a metal electrode. The TCO layer is used to collect electrons, and the HTM layer is used to collect holes. The metal electrode is used to extract the collected charge carriers from the device.

6.Characterization and optimization: The final step in the processing of QDSCs involves the characterization and optimization of the device. Characterization techniques such as UV-Vis spectroscopy, photoluminescence, and current-voltage measurements can be used to evaluate the performance of the QDSC and optimize its properties for maximum efficiency.

IV. USE OF QUANTUM DOTS IN BUILDING SOLAR CELLS

Solar cell construction could undergo a revolution thanks to quantum dots. The efficiency and cost-effectiveness of solar cells can be increased by using these tiny semiconducting particles. The ability to tune quantum dots is one of their main benefits for solar cells. The wavelength of light that the quantum dots absorb can be changed by adjusting the quantum dots' size. In contrast to conventional solar cells, which can only absorb a certain range of solar radiation, they can be optimised to capture a wider range of solar radiation.

Furthermore, multiple excitons can be produced from a single photon using quantum dots. The efficiency of solar cells can be significantly improved through this multiple exciton generation (MEG) process. Each photon that is absorbed by conventional solar cells results in the generation of just one electron. To increase the cell's current output, MEG allows for the generation of multiple electrons for every photon. The price of producing solar cells may be decreased by quantum dots as well. They are easily scalable for mass production and can be produced using low-cost, solution-based processes. Additionally, because flexible substrates can be printed with quantum dot solar cells, they are perfect for use in portable electronics.

Before quantum dot solar cells can be widely adopted for commercial use, there are still a few obstacles that need to be cleared. Their stability and durability are among the main problems. The long-term performance of the solar cell may be impacted by the susceptibility of quantum dots to deterioration over time. To address this problem, scientists are presently working to create more stable quantum dot materials

By fusing novel nanoscale properties with low cost and processability to enhance solar energy conversion, QDs offer new methods for effective photoexcitation and charge separation. To include QDs in solar cells, three general approaches have been suggested. Wide-bandgap semiconductors are sensitised using the QDs in the first approach. The second tactic involves putting the QDs in close proximity to electron- or hole-conducting polymers. The third tactic involves creating QD arrays in which the QDs are electrically connected to enable effective electron/hole conductivity.

In order to achieve charge separation and transport, the first two strategies rely on the QDs acting as the light-absorbing component in close contact with other materials. The highly coupled QD-array is required for light absorption in the third strategy.

A.Hot Carriers to Increase Solar Cell Efficiency

Hot carriers in solar cells transform excess photon energies into stable forms before excited states can achieve an equilibrium state with the surrounding environment. In semiconductors and molecules, respectively, this extra photon energy manifests as the kinetic energy of the carriers and is dissipated as heat. When a photon with an energy above the bandgap strikes the cell, the electrons become excited, and thermalization takes place via phonon-carrier scattering.

B.Tandem Solar Cells

Two or more solar cells are stacked on top of one another to form tandem solar cells, a type of photovoltaic device. Multiple solar cells are stacked to increase the device's overall effectiveness. In tandem solar cells, the top cell is typically made to absorb photons with higher energy while the bottom cell absorbs photons with lower energy. As opposed to single junction solar cells, which are restricted to a particular range of wavelengths, the tandem cell is able to capture a wider range of the solar spectrum as a result.

Series-connected, monolithic, and mechanically stacked cells are a few of the different varieties of tandem solar cells. The current output of one cell feeds into the next in tandem cells that are connected in series. Mechanically stacked cells are created by stacking individual cells one on top of the other, as opposed to monolithic tandem cells, which are created from a single piece of material with multiple junctions. With some designs, tandem solar cells can have efficiencies that are over 30%, making them significantly more efficient than single-junction solar cells. Tandem solar cells also have the potential to use a wider variety of materials, including ones that are not typically used in solar cells.

Tandem solar cells, however, also come with some difficulties. The fact that they can cost more to produce than single-junction solar cells is one of the main problems. Additionally, factors like optical losses and current matching between the various cells may be able to restrict the efficiency gains from using tandem solar cells. Despite these difficulties, research on tandem solar cells is ongoing, and there is a lot of interest in creating new materials and designs to boost their functionality and lower their cost.

V. CURRENT RESEARCH INITIATIVES ON QUANTUM DOT SOLAR CELLS

There are currently several research initiatives focused on developing quantum dot solar cells with improved efficiency, stability, and scalability. Here are a few examples:

1.Improved Quantum Dot Materials: Researchers are working on developing new quantum dot materials that are more stable and efficient than existing materials. This includes using new materials, such as perovskites, that have shown promise in other types of solar cells.

2.Tandem Solar Cells: Tandem solar cells that incorporate quantum dots are also an active area of research. These cells use a combination of different types of solar cells to capture a wider range of the solar spectrum and increase efficiency.

3.Passivation Techniques: One major challenge with quantum dot solar cells is their instability and degradation over time. Researchers are working on developing new passivation techniques that can improve the stability and longevity of quantum dot solar cells.

4.Solution-based Manufacturing Processes: Solution-based manufacturing processes, such as inkjet printing and roll-to-roll processing, offer a cost-effective and scalable way to manufacture quantum dot solar cells. Researchers are working on developing new processes that can improve the efficiency and stability of solution-based quantum dot solar cells.

5.Upscaling Manufacturing: Researchers are also exploring ways to scale up the manufacturing of quantum dot solar cells for commercial production. This includes developing new manufacturing processes that are compatible with existing solar cell production lines and improving the overall cost-effectiveness of the technology.

VI. CONCLUSIONS

The next generation of PV modules is said to use QD-based solar cells. These assert to offer greater efficiency than conventional solar cell modules, primarily through multi-exciton generation, utilisation of the unabsorbed part of the spectrum, and decreased heat dissipation. These assertions notwithstanding, no practical device has been suggested. This is as a result of the five physics-based fundamental criteria listed below: We cannot ignore the interactions between charge carriers and phonons first. Second, the solar cell's top layer produces hot carriers. Thirdly, the functioning of solar cells has nothing to do with the phenomenon of photoluminescence. Fourth, recombination of the intermediate bandgap reduces the performance of solar cells. Finally, a material's ability to transfer heat from the device requires a high degree of thermal conductivity for practical applications. QDs, however, are an exception to this.

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