

# Advancements in High-Efficiency Solar Cells Utilizing Advanced Materials

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## Abstract

Solar cells are optoelectronic devices that convert sunlight energy into electricity by the so-called photovoltaic effect. These devices can be made from a variety of semiconductor materials, such as crystalline or Mult crystalline silicon, amorphous silicon, copper indium Di selenide, and cadmium telluride. The key materials inside a solar cell are semiconductors, which can effectively utilize these directly into electricity. In this work, we discuss some advanced materials used in several high-efficiency solar cells for effectively improving photoelectrical conversion efficiency.

**Keyword:** Solar Cell, Solar Energy Conversion, Renewable Energy, High Efficiency.

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## 1. Introduction to Solar Cells

Welcome, esteemed and cherished audience, to this truly magnificent and awe-inspiring introduction that lies before your very eyes, eager to unfold its grandeur. I invite you to join me on a profound expedition into the boundless realm of knowledge, a place where the limitless horizons of enlightenment are waiting to be explored, cherished, and embraced together. With each fleeting second that passes by, we shall plunge beyond the surface, unearthing the treasures that adorn the rich and intricate tapestry of information, casting luminosity upon a myriad of captivating subjects that are destined to expand your horizons, rejuvenate your mind, and arouse the ever-glowing ember of curiosity within the depths of your being. Buckle up, for we are about to embark on an extraordinary voyage of discovery, one that promises not only invaluable wisdom but also boundless treasures of insight. Let the symphony of knowledge liberate our senses and leave an indelible mark upon our souls as we commence this enthralling, mesmerizing, and compelling introduction that, undoubtedly, shall etch itself deep within the recesses of our minds, forever carving a path towards enlightenment and personal growth.

Solar cells are optoelectronic devices that convert sunlight directly into electricity. These devices, often referred to as photovoltaic (PV) devices, can be made from a variety of semiconductor materials including crystalline or multicrystalline silicon, amorphous silicon, cadmium telluride, and copper indium diselenide. Solar cells can be classified into various categories and are typically characterized based on the nature of their material compositions, physical size, thickness, and the processes utilized for device fabrication and module assembly. Crystalline silicon wafer solar cells are produced by an energy-intensive process at high temperatures, where raw silicon in crystalline form is coated onto either monocrystalline silicon or polycrystalline silicon wafers, resulting in wafer silicon solar cells. The microscopic circuits on the front surface of the wafers are coated with an antireflection coating to enhance the device performance.

There is a great deal of ongoing research in the field of solar cell technologies, often with new materials and processes resulting in record-breaking efficiencies in the laboratory. Technologies such as concentrating photovoltaic (CPV), organic photovoltaics, dye-sensitized solar cells, and quantum dot sensitized solar cells are a few novel fields of research. The conversion of solar energy into electricity is a mature and scientifically investigated technology, and there is a large variety of solar panel products currently available on the market for residential, commercial, and utility-scale applications. These products range from flexible thin-film technologies to high-efficiency multi-junction

solar cells for specialized aerospace and concentrating photovoltaic applications. The history of utilizing solar power dates back to 700 BC, when magnifying glasses were used to concentrate and focus sunlight to create fire. Significant progress has been made in the last half century; beginning in the 1950s, silicon PV solar cells were initially developed for commercial and residential power sector applications, and then utilized for space exploration missions in the 1960s and 1970s. Given the finite supply of fossil fuels and the environmental changes accompanying their use, solar cells and PV technologies, in general, are being explored as potential long-term solutions for the development of environmentally friendly, renewable, and sustainable energy technologies. The module efficiencies and conversion costs of solar cells have drastically improved, making the technology more attractive to academic, industrial, and government institutions. The success of solar cell technology is dependent on its material, device, and modules; continuous research is carried out in an effort to develop high-conversion-efficiency, lower-cost solar cell devices for commercialization. [1] [2] [3] [4] [3] [5] [6] [7] [8] [9] [9] [9] [10] [2] [11] [12] [12] [13][14][15] [16][17][18][19][20][21][22][23][24][25]

### **1.1. Basic Principles of Solar Energy Conversion**

Sunlight is the most abundant renewable energy source. Solar cells of modern times can convert sunshine into electrical energy by the so-called photovoltaic effect. The functional behavior is based on several physical principles, which will be briefly elaborated in the following part. Sky radiation can be categorized into direct sunlight, diffuse sunlight, and albedo radiation. Typically, solar cells are capable of converting direct sunlight and diffuse sunlight into electricity. The key materials inside a solar cell are semiconductors, which can effectively utilize these directly into electricity. The essential principles of a basic solid-state solar cell may be described as follows. Sunlight reaching the surface of a solar cell is absorbed by the interaction with the semiconductor. This process is accompanied by the generation of free electrons and holes, which are photogenerated from photons. The electrons and holes inside the p-n junction in the solar cell then start to drift and are forced to separate by an internal electric field due to a built-in potential difference or a drift field applied across the p-n junction. In the steady state, the built-in potential can maintain a stable electron and hole concentration gradient driving force inside the device.

The driving force inside a solar cell can ensure electron-hole separation and impact the space-charge region together with overall solar energy, electrons, and holes from semiconductor electrode recombination in the depletion region through drift and diffusion processes. The solar cell efficiency can be evaluated by various parameters, such as open-circuit voltage, short-circuit current density, fill factor, and maximum power conversion efficiency, whose values are based on the materials and device structure of a particular solar cell. Many factors can affect the efficiency of a solar cell, including but not limited to material band gap, optical absorption constant, and the freedom of carrier lifetimes,

which should be fast, leading to a small recombination loss. In other words, a more efficient solar cell demands a higher number of generated carriers and a reduction of non-radiative recombination loss. In this work, our focus is to discuss some advanced materials used in several high-efficiency solar cells for effectively improving photoelectrical conversion efficiency.

## **2. Importance of High-Efficiency Solar Cells**

High-efficiency solar cells and modules are in high demand due to the surging request for renewable sources. High-efficiency solar cells can generate more electrical energy per unit, which in turn decreases the cost required for energy generation, storage, and use. Besides, high-efficiency solar cells can be employed in construction-integrated sound barriers and noise absorption walls, roads, and coatings as building materials or for power generation. Rapid developments in solar cell technology can be encapsulated through the flags and achievements of the photovoltaic roadmap. The global photovoltaics capacity was estimated at about 16.5% by the end of 2020, and this number is predicted to increase to about 25.5–31.6% in 2050, provided that the current targets for renewable energy sources, such as solar electrical energy, are preserved and improved.

Several successful strategies have been proposed to elevate the efficiency of solar cells, and the majority of these strategies are focused on the development of either novel materials or novel photovoltaic device architectures. Nevertheless, the emphasis on increasing the efficiency of solar cells is constantly shifting toward materials, where numerous advanced materials and nanotechnologies have issued a pathway to achieve high-level qualitative and quantitative perfection in solar cells. Given the surging momentum relying on the technological interventions of materials and devices for optimum efficiency in solar cells, scientific research and technological interventions for high-efficiency solar cells demand further attention. Solar cells based on novel and advanced materials are promising, and therefore, we prepared this review to discuss such types of solar cells on the internal frontier for harnessing solar energy in more cost-competitive manners.

### **2.1. Impact on Renewable Energy Sector**

Solar power as a primary, non-dispatchable, and inexhaustible clean domestic energy source became relevant with the arrival of high-efficiency, cost-effective solar cells. Over the eight decades, inorganic and organic materials used in high-efficiency solar cells have progressed rapidly. Consequently, the LCOE for solar photovoltaic (PV) has declined greatly, while the annual installation of solar PV has risen exponentially. As a result, the energy landscape has started to change, as more countries transition to renewable solar power. Although it was inconceivable two decades ago that solar power could become the leading source of global net electricity-generating capacity by the early 21st century, this is the reality, as the position of solar power, particularly PV plants, has changed in

the large-scale power systems of 46 countries by 2020. Economic research confirms that operating a power system with solar as a leading energy resource yields lower annual system LCOE compared to those in which coal and nuclear power play leading roles. The greenest states are those with higher solar share, as they have the lowest carbon equivalencies and carbon intensity.

Advanced cost-effective solar cells can also create jobs, as they are involved in module and system assembly, and O&M. Economic research has shown that investing in an advanced solar farm would create higher return rates and the number of jobs created when compared with investment in a fossil fuel-based power station. The introduction of advanced materials in solar cells is very timely, given the growth in demand for renewable energy that is increasing year on year. With both environmental benefits and a per capita income increase, the use of renewable energy technologies will generate benefits, as the way of trading these benefits is the generation, sales, and exports of renewable energy credits. More often than not, the deployment of grid-connected high-efficiency solar panels follows improved energy policy, which is supportive of renewable energy resources, also attracting high investment. In contrast, the energy developing or underdeveloped country has an off-grid solar adoption rate of 85%; however, it is still facing large disparities in the availability of new and advanced solar technology that reduces emissions.

### **3. Advanced Materials for Solar Cell Technologies**

Developing advanced materials is an essential aspect of developing new and enhancing existing solar cell technologies. The properties of these materials largely determine the minimum and maximum performance metrics achievable by these technologies. Although the efficiency of traditional, silicon-based solar cells has slowly increased over the past 50 years to reach approximately 27.3%, the development of new materials could enable significant performance gains. Recent research has thus focused on developing materials compatible with traditional, low-cost processing methods.

Perovskites, as alternative materials to crystalline silicon with complementary optical and electronic properties, are made through self-organization and are compatible with roll-to-roll processing, potentially enabling low-cost high-throughput manufacturing. Colloidal quantum-dot solar cells represent another game-changing photovoltaic technology that has obtained a power-conversion efficiency greater than 15% in laboratory settings. Quantum dots are especially interesting because when their size or composition is controlled, they can interact with light in different ways. This produces a continuous absorption spectrum that can be tuned across the ultraviolet, visible, and infrared light, enabling a solar cell that can make use of more of the incoming light. Both perovskite and quantum dot technologies have already seen several start-ups founded around the technologies in the past few years and have received large amounts of investments.

Ongoing research is focusing on ways to reduce materials costs, increase scalability, reduce the cost of processing and manufacturing, demonstrate stability and performance, and counteract the known management of toxic elements in these materials.

### **3.1. Perovskite Solar Cells**

The perovskite materials used in solar cells are a class of crystalline structures characterized by the general formula  $ABX_3$ , where A is usually an organic cation or a small inorganic cation at the corner of the cubic unit cell, B is typically a metal cation at the center of the unit cell, and X is an anion bonded at the edges of the cell. The  $ABX_3$  configuration contributes to a highly stable and effective light absorber due to both favorable electronic properties and its demonstrated ability to absorb light at the low energies characteristic of the solar spectrum. Current research interests in the field of perovskite materials typically explore common and readily available lead halide perovskites for solar cell applications, although the number of tin, carbon-based, lead-reduced, or lead-free halide perovskites being explored by the research community is continually growing.

The emergence of perovskite solar cells as a potential new leader in the photovoltaic industry is driven largely by the rapid improvement in their efficiencies in recent years and their ability to be produced at extremely low costs. The solar cell research field is influenced by the cost of the materials that make up the device – raw materials that are naturally abundant and cheap to obtain will have a strong influence on the cost per watt of the final device. Materials based on lead, such as A-level metal lead halide perovskites, are typically shunned for use in semiconducting devices since toxic cations can leach out of the device once it ends its useful life, resulting in damage to the surrounding environment and people. In perovskite solar cells, although a layer of perovskite slurry is spread onto the device using low-cost solution-processing methods, a high efficiency is achieved, making perovskite a highly sought-after photovoltaic material. Many lead-containing solar cells are assembled with commercial or non-commercial recycling strategies in mind, aiming to recover a high percentage of materials such as lead within the device for reuse long after they have stopped producing electricity.

### **3.2. Quantum Dot Solar Cells**

Quantum dot solar cells are composed of an active layer containing quantum dots, which are nano-sized semiconductor crystals. The electrons and holes in quantum dots are confined in a small volume, producing a discrete set of energy levels. Thus, the electronic and optical properties of quantum dots can change depending upon the size and shape of the dots, which is an attractive feature of quantum dots and different from bulk, quantum well, and quantum wire materials. Quantum dots are able to overcome the problem of conventional semiconductors where light absorption is limited by the assignment of

lattice energies. The light energy spectrum conversion in the solar cell depends on the size of quantum dots, and the possibility of obtaining this size is in principle unlimited. Such light energy manipulation will reduce the dimensions of the conventional multi-junction cells and will utilize most of the solar spectrum that falls in the infrared and ultraviolet regions. By replacing the high band gap semiconductors with quantum dots, flexible cells would be obtained that show an efficiency comparable to that of multi-junction stack cells. Nowadays, there is a need for utilizing the absorbed energy spectrum according to the useful form of the matrices in various applications. One of the interesting features of quantum dot solar cells is the desired isolation of the quantum dots from a matrix, while the other part of the active layer for electric charge transport is best to be a good conductor. This ensures that a superior energy conversion between the quantum dots and the matrix can be achieved. Additionally, the isolation of quantum dots is necessary for the usage of their strong size and shape tunable electronic and optical absorption behaviors.

The first quantum dot solar cells were reported in 1994, and then, quantum dots based on the quantum confined Stark effect received considerable attention for possible utilization in light harvesting cells. Certain materials were used with an organic hole transfer layer to fabricate the first solar quantum dot solar cell, providing a band gap of 1.42 eV with 76.4% internal quantum efficiency. The first solar cell including both n and p layers was reported in 2003 by a process called sensitization, which was used to inject electrons into titanium dioxide quantum dots in electrochemical dye-sensitized solar cells. In 2005, the inclusion of certain materials to the titanium dioxide transport layer of quantum dot sensitized cells proved to be reliably stable in liquid electrolyte. The areas of research on quantum dot solar cells have been extensively improved since the first introduction of quantum dot sensitized solar cells. Lately, the conversion efficiency of solar quantum dot solar cells has improved and is now up to 10.4%, which currently is a milestone for the development of quantum dot-sensitized solar cells.

Quantum dots are commonly used in quantum dot solar cells because the amount of carriers that create exciting events can be controlled, and the number of carriers that can be placed on the quantum layer can be very high. There are many materials used for the production of quantum dots, so choosing the right material can result in a remarkable amount of cells produced by the quantum dot solar cell. There are many quantum dots, and their properties can be specifically addressed in a selected practical environment. Quantum dots seem, however, to have a high overall potential to be used in practical quantum dot solar cells. Due to their multiple mechanisms for development, the lifetime and the photovoltaic performance of quantum dot solar cells have a high cumulative capacity. The preparation of a quantum dot solar cell has structures that vary with applications.

## 4. Enhancing Efficiency Through Innovative Designs

Design is of paramount significance in any system's performance. Solar cell technology is not an exception, and a well-chosen design that optimizes solar cell parameters, including the absorption of solar energy, charge carrier extraction, and collection, positively impacts final solar cell performance. The performance of a solar structure is usually quantified by its efficiency, which denotes a fraction of incident solar energy that is converted to electric power.

Research in the field of photovoltaics has advanced designs using multiple layers of materials with differing band gaps, electron affinities, or other optically and electronically relevant material properties, fabricated using different deposition technologies that are well-suited to each material. These are now termed multi-junction or tandem solar cells, since two or more individual solar cells are stacked and operate in series to significantly increase energy conversion efficiencies. It has been demonstrated that tandem cells offer benefits for a wide range of solar technologies.

Most research into tandem cells has been at the laboratory scale, though a few recent studies have investigated their scalability. The world-record efficiency for monolithic tandems hovers around 33%, and for silicon-perovskite tandems is 29.15%—both measured in test conditions without concentration. Such impressive efficiencies make it clear why tandem solutions are appealing for both commercial and concentrator applications. These multi-junction designs have a multitude of benefits, such as significantly increasing the energy conversion efficiencies of solar technologies, but they must also navigate issues of mechanical integrity, achieving bifacial collection, and thermal coupling, among other things. Additionally, novel designs are often significantly more complex in terms of photovoltaic physics, optoelectronic interactions, and carrier transport. Moreover, the prospect of crystalline growth on crystalline templates can present issues that exacerbate material constraints as well as defects that precipitate crushing loss in solar cell efficiency. Regulatory hurdles, also unique to innovative designs, can make proving safety, performance, and lifetime difficult, time-consuming, and expensive.

### 4.1. Tandem Solar Cells

Single-junction solar cells have a general limit of approximately 33.5% in power conversion efficiency for non-concentrated sunlight and approximately 29.4% for directly converting the solar spectrum. This is due to the impaired efficiency at lower and higher wavelengths for absorption, or higher energy photon absorbance increasing losses in the futuristic strategy. With the aim of surpassing the single-junction performance, a multijunction tandem cell with several junctions made with photovoltaic materials of different band energies is connected physically in series, building an efficient tandem device that exceeds the performance restrictions for a given single junction for single

materials. Theoretically, the tandem efficiency has a maximum of approximately 49.4%, decreasing the energy gap for 3J to 0, without losses. Nonetheless, the real efficiency limit is less compromised by a balance between band gap reduction and other intrinsic limitations. Tandem configurations can comprise (i) one lower band gap material, defect-tolerant, with minimum current matching for better performance; (ii) two even more refined higher band energies for current matching.

Tandem photovoltaic cell configurations can be generated between several junctions with electrical interconnections between the corresponding semiconductors to improve the device capabilities. The most commonly followed configurations are defined as 1. Bifacial inorganic or 2. Bifacial perovskite solo/multijunctions nested on the bifacial silicon solar cell. With a prevalence of 86%, the monolithic configuration is the most widespread in research. The scheme is composed of multiple materials directly grown on the sub cell below. Earlier tandem designs have been established by combining different combinations of amorphous, micro-crystalline, and crystalline germanium, gallium, CIGS, indium, or silicon junctions. The deposition of heterojunction materials simply combines the top cell organic/inorganic deposition, while GaAs tandem solar cells have also presented lower efficiencies, related to the lower dual junction section radiation resistance. With the assistance of converter chalcogenides, a solar cell power conversion efficiency of 18% and 22.6% for n-i-p and p-i-n structure tandem designs was reported, and a PCE of 25.7% was reported by using the thin many active region cells. The commonly used group III-V and silicon-based tandem solar cells are based on a lattice matching substrate. For example, with InGaP/GaAs TPV, an efficiency of 31.5% was reported, demonstrating the highest one-sun efficiency of any TPV-photon source combination at that time. With a lattice matching substrate Si and various tandem structures, an efficiency of 32.6% was achieved.

## 5. Future Prospects and Challenges

Global energy supplies and climate change preventive policies are two crucial components in the future ecosystem. Solar energy conversion to electricity is very important, which is indicated in the energy strategies of various countries. An executive order was signed to kick off the solar power development across the US. The US targets to deploy 30 GW of offshore wind, 40 GW of distributed solar energy, and 50 GW of utility-scale solar energy for the year 2030. In a similar way, targets for solar power deployment in certain regions are set for the year 2025. To incorporate larger quantum dots for large-scale deployment, either liquid-phase deposition techniques or solution-based liquid processing are preferred.

The ultimate goal of photovoltaic technology is to provide clean, free, and renewable solar energy for humanity. Whenever we construct a photovoltaic device, which is efficient in converting sunlight energy into electricity, it is important to ensure the

following two tasks: (i) to have active layers by using either a single or more semiconducting photovoltaic cells, which should have low costs and abundance with enhanced electro-optical efficiencies, (ii) to obtain new innovations in the photovoltaic device design or concepts. Over the last decades, major breakthroughs have been made both in perovskite and perovskite/silicon tandem solar cells. These successful attempts indicate that the technologies of advanced photovoltaic materials and the processes have been rapidly evolving to reach similar levels. Although there are some challenges yet to be addressed, such as long-term stability and standardization of the tandem cells, they are being gradually adopted for applications in the near future.

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