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Nanotechnology and its Applications in Solar Cells

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Abstract - *Due to a significant interest in renewable energy and the challenge of global climate change, the solar cell sector has developed rapidly in recent years. The cost of any solar technology is critical to its success. Today's solar cells are just insufficiently efficient and too expensive to manufacture to make them economically viable for large-scale power generation. On the other hand, potential advances in nanotechnology may pave the way for the manufacturing of cheaper and somewhat more efficient solar cells. Nanotechnology is a field of science and technology of controlling matter on a nanoscale. Nanotechnology has already made significant advances in the field of solar energy. Third generation solar cell like Quantum dots and Dye-synthesized solar cells have the power to alter the course of history. They're the type of solar cells that's unlike anything we have ever seen before. Although nanotechnology has the potential to improve solar cell efficiency, the most promising application of Nanotechnology is to reduce the cost of production. PVs based on CdTe, CuInSe (CIS), CuInGaSe (CIGS), CuInGaSe (CIGS) and organic materials are being developed to lower the price per watt, even if conversion efficiency and reliability are sacrificed. Nanotechnology in low-cost solar cells would aid in environmental preservation.*

Key Words: Solar Cells, Nanotechnology, Renewable Energy, Quantum Dots, Dye-synthesised Solar Cells.

1. INTRODUCTION

Solar panels are one of the most popular forms of renewable energy. Individual houses and companies are increasingly using them to generate their power, particularly in warmer regions and more eco-conscious countries like Germany.

Conventional solar cells are called photovoltaic cells. Generally, silicon semiconductor is used to make these cells. When light hits the cells, they absorb energy through photons. This absorbed energy knocks out electrons in the silicon, enabling them to flow. An electric field can be created by adding various impurities to silicon, such as phosphorus or boron. Because electrons can only flow in one way, this electric field functions as a diode. As a result, a stream of electrons is produced, which we know as electricity.[1]

Photovoltaic (PV) cells convert solar energy into an electrical voltage. These are made up of multiple layers of materials, each having its own set of characteristics that are best suited to the task at hand. Advances in the materials used in PV cells will drive down the cost of solar panels, allowing them to be utilized more widely in household, industrial, and grid-level applications.

The main aims of R&D for PV technologies are:

- increase the light absorption rate
- increase the efficiency of the photovoltaic effect
- decrease the cost of manufacturing
- make PV cells adaptable to different scales and localities

1.1 Three Generations of Solar Panels:

Photovoltaic technology has been categorised into three distinct generations, each representing a significant advancement in the materials and manufacturing processes used to create the cells.

The first generation of solar cells is made of crystalline silicon of extremely high quality. These are costly to produce and have a theoretical efficiency ceiling of just about 33%.

Second-generation PV cells use thin-film technologies with other semiconducting materials such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). These materials offer substantially better theoretical efficiency than silicon-based PV materials, and they can dramatically lower manufacturing costs.[2]

Third-generation PV refers to a wide range of technologies that are either new or in the early stages of development. Quantum dots, nanostructured semiconductors, and amorphous silicon are all considered third-generation technologies.

1.2 The Role of Nanotechnology

Nanotechnology can assist in the development and production of second-generation thin-film PV cells. On the other hand, nanomaterials will truly shine in the third generation of solar cell technologies when innovative technologies such as nanowires, quantum dots, and radial junctions begin to push PV efficiency to new heights.

Nanostructures may also make it possible to make effective solar cells out of less expensive, more common materials like silicon and titanium dioxide. Although there will be costs associated with establishing mass-production techniques for nano-enhanced PV cells, the utilization of lower-cost raw materials will allow commercial solar cell prices to continue to fall.

The nanomaterials applied in solar energy conversion may be classified into different classes depending on the application. Photocatalysts are a big family used in water treatment, CO2 reduction, hydrogen production and much more.

In all the systems, the tech is based on solar energy transformation or utilization. The efficiency of systems is dependent on the size, active area and particle distribution. Nanoparticles exhibit many useful properties, including an active surface state, low bulk density, and unique photoluminescent and biocompatible properties, the cause of which they are integrated into solar cells.

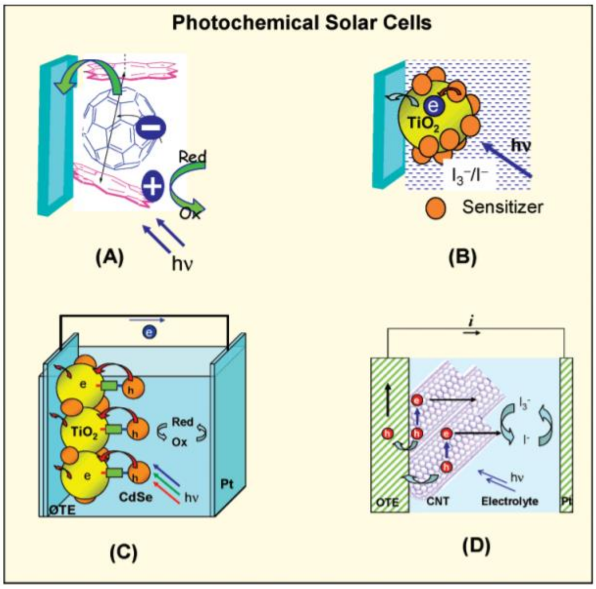

Fig-1: Strategies to utilize nanostructures in photochemical solar cells

2. LITERATURE REVIEW

Solar cells cannot convert all incoming light into usable energy as some light can escape back into the air. Furthermore, sunlight comes in various colours, and the cell may be more efficient at converting bluish light than it is at converting reddish light. Lower-energy light remains unused as it passes through the cell. Higher-energy light does excite electrons into the conduction band, but any energy beyond the bandgap is wasted as heat. If the excited electrons aren't captured and redirected, they'll spontaneously recombine with the newly formed holes, releasing the energy as heat or light.

UV radiation is either filtered out or absorbed by the silicon in conventional solar cells, where it is transformed into potentially harmful heat rather than electricity. Ultraviolet light could efficiently couple to correctly sized nanoparticles. Integrating a high-quality film of silicon nanoparticles with a diameter of 1 nanometer directly onto silicon solar cells boosts power output by 60% in the ultraviolet region.[3]

The radius in bulk material is significantly less than that of a semiconductor crystal. Nanocrystal diameters, on the other hand, are lower than the Bohr radius. As a result, the electron energy levels' "continuous band" can no longer be considered continuous.

Quantum confinement is observed as the energy levels become discrete. The difference of a few atoms between two quantum dots alters the band gap boundaries. Larger nanocrystals absorb longer wavelengths or redder light, whereas smaller nanocrystals absorb shorter wavelengths or bluer light. The bandgap energy level fluctuates as the shape of the dot changes.

Quantum-dot-sensitized solar cells (QDSSCs) provide additional opportunities that are not available with dye-sensitized solar cells [4]. First, using quantum dots allows you to tune the optical absorption in a solar cell by selecting the right semiconductor material and particle size. Second, QDSSCs can potentially exploit the recently observed multiple electron-hole pair generation per photon to achieve greater efficiencies than Shockley and Queisser expected.[5]

The researchers began by converting bulk silicon into discrete, nano-sized particles to create more efficient solar cells. The required size nanoparticles were then dispersed in isopropyl alcohol and dispensed over the solar cell's face. As the alcohol evaporated, the solar cell was left with a film of tightly packed nanoparticles.

Solar cells coated with a layer of 1 nanometer blue luminescent particles exhibited a power enhancement of around 60 per cent in the ultraviolet region of the spectrum but less than 3 per cent in the visible range. Solar cells coated with 2.85 nanometer red particles exhibited a 67 percent enhancement in the ultraviolet range and about ten percent enhancement in the visible range.

Ultra-thin films of highly monodispersed luminescent Si nanoparticles are directly integrated on polycrystalline Si solar cells. In the UV/blue region, films of 1 nm blue luminescent or 2.85 nm red luminescent Si nanoparticles provide significant voltage enhancements and increased power performance of 60%. The enhancements are ~3% for the blue particles and ~10% for the red in the visible region. [6]

Electrons produced in a nanoparticle-based solar cell must travel a circuitous path (red line) as shown in Fig-2 to reach an electrode. Many do not make it, which reduces the effectiveness of these cells. Notre Dame researchers used carbon nanotubes to help electrons reach the electrode, increasing the efficiency of the solar cell.

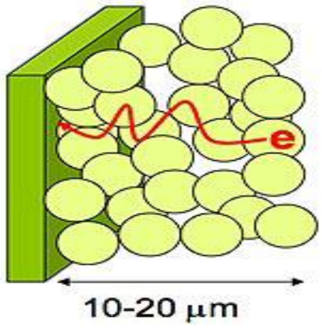

Fig-2: Path of electron

Without the carbon nanotubes, electrons generated when titanium-oxide particles absorb light have to jump from particle to particle to reach an electrode. Many are not able to create electric current. Carbon nanotubes "collect" electrons and provide a more direct path to the electrode, increasing the solar cell's efficiency.[7]
The combination of two or more nanostructure architectures provides another option to modulate the performance of light-harvesting devices [8]. The electron transport across particles is susceptible to recombination loss at the grain boundaries and charge trapping in nanostructured semiconductor films prepared from particles. The use of nanotube/nanowire support to anchor light-harvesting assemblies (*e.g*., semiconductor particles and dye molecules) provides a convenient way to capture photogenerated charges and transport them to electrodes.

3. MATERIALS AND METHODS

Nanotechnology can be used for improving performance, efficiency and cost of second-generation thin-film PV cells and third generation PV cells.

3.1 Drawbacks of Conventional solar Cells (First generation PV cells)

Conventional silicon cells have two major drawbacks: their low efficiency (approximately ten per cent) and their high production costs. With silicon cells, the first disadvantage, inefficiency, is almost inescapable; this is because light/incoming photons must have the right energy for electrons to jump across the band gap. If the photon has less energy than the band gap energy, then it will pass through. If the electron has more energy than the band gap, then the extra energy will be wasted in the form of heat. These effects are responsible for the loss of 70% of the radiation energy incident on the cell. [9,13]

3.2 Nanotechnology and Thin-Film Technologies (Second Generation PV cells)

Nanotechnology can help in the design and manufacture of thin-film PV cells. It can also be used to manufacture less expensive solar cells from conventional materials, like silicon. Nanoparticles are many times smaller than the width of a hair. Because of its size, a large number of nanoparticle atoms reside on the surface instead of the interior, which increases their surface interaction.

They offer significant three advantages over ordinary solar cells:
First, the effective optical path for absorption is significantly greater than the actual film thickness due to multiple reflections.
Second, light-generated electrons and holes need to travel a considerably shorter path, reducing recombination losses significantly. As a result, in nanostructured solar cells, the absorber layer thickness can be as low as 150 nm, compared to several micrometres in typical thin-film solar cells.
Third, by adjusting the size of nanoparticles, the energy band gap of various layers may be adjusted to the required design value. This provides for greater design freedom in the absorber of solar cells.[10]
Thin-film is a more cost-effective approach that employs a low-cost support on which the active component is applied as a thin coating. Consequently, far less material is used (as less as 1% compared to wafers), and hence costs are reduced. The majority of these cells use amorphous silicon, which, as its name implies, does not have a crystalline structure and consequently has a much lower efficiency (8%) but is significantly cheaper to produce.[11] Therefore, according to the Lawrence Berkeley National Laboratory, today's maximum efficiency is around 25 per cent [12], much greater than mass-produced solar cells, which usually achieve only ten per cent efficiency.

Second-generation solar cells have some drawbacks, including the toxicity of certain materials used (e.g., Cd) and limited abundance (e.g., In and Se) of component materials. Furthermore, they must be made more efficient to make them commercially viable.[14]
Both the first- and second-generation solar cells are based on single-junction devices, which must obey the Shockley-Queisser limit with a maximum thermodynamic efficiency of 31–33 % when the optimum band gaps fall between about 1.1 and 1.4 eV.[15]

3.3 Third Generation Solar Cells

Third-generation solar cells like hot carrier cells, Tandem cells, dye-sensitized solar cells, and organic solar cells can overcome this thermodynamic efficiency limit. The most significant point is that these third-generation solar cells promise to convert solar energy into electricity at a low cost, less than $0.5 per watt-hour. [16,17]

3.3.1 Dye-Sensitized Photovoltaic Cells / Dye-Sensitized Solar Cells (DSSC)

Among these third-generation solar cells, DSSCs have many appealing qualities that make them highly marketable. They offer low production costs (i.e., low embodied energy, the possibility of roll-to-roll processing), low toxicity, earth-abundant materials (except Ru and Pt), good performance in a variety of light conditions (i.e., low-intensity, partial shadowing and high angle of incidence), flexible, lightweight, and design feasibility (i.e., transparent, selected colors and bifacial). [16,18]
DSSCs have evolved into a strong photovoltaic technology with a reported efficiency of 12.3 per cent after two decades of intense work.[19]

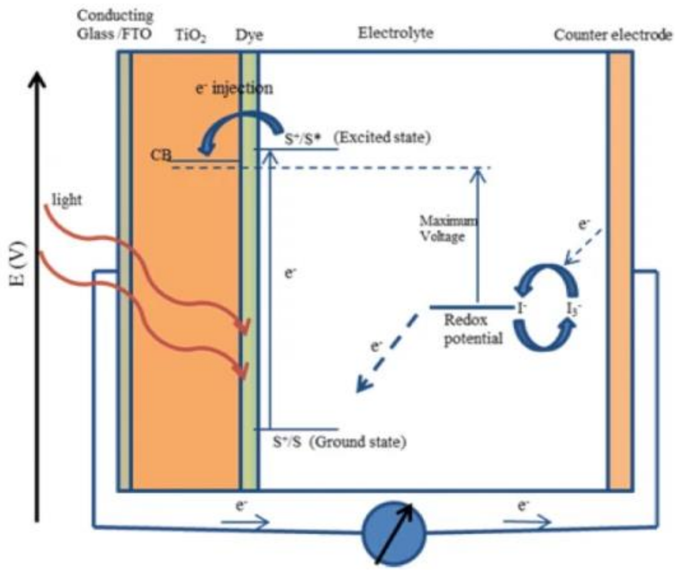

Fig-3: Structure of DSSC

A DSSC is generally made up of five components: a semiconductor film (e.g., TiO2), conductive mechanical support (e.g., transparent conductive glass or Ti foil), an electrolyte (e.g., iodide/triiodide couple), a sensitizer (e.g., ruthenium dye N719), and a counter electrode (e.g., Pt-coated electrode).

A semiconductor film on which a monolayer of visible light absorbing dye is chemisorbed generates electricity. Photo-excitation of the absorbed dye molecules generates excited electrons that are further injected into the semiconductor's conduction band and quickly migrated to the external circuit through the conductive substrate. Electron donation from the electrolyte, which is generally an organic solvent with a redox system, such as the iodide/triiodide (I^-/I^-_3) pair, restores the dye's original state. [20,21]

The difference between the Fermi level of the electron in semiconductor materials and the redox potential of the electrolyte determines the voltage created under illumination. [20,22]
The nanoporous semiconductor, which is primarily made of TiO_2 components and serves as an electron acceptor and electronic conductor and provides many adsorption sites for the dye sensitizer, is the system's heart. [13]

Working Principle

The working principle of DSSC involves four basic steps: light absorption, electron injection, transportation of carrier, and collection of current. The following steps are involved in the conversion of photons into current:

1. Firstly, the incident light (photon) is absorbed by a photosensitizer. As a result of photon absorption, electrons are promoted from the dye's ground state (S+/S) to its excited state (S+/S*), where most of the dye's absorption is in the 700 nm range, corresponding to a photon energy of nearly 1.72 eV.
2. After this, excited electrons with lifetime of few nanoseconds are injected into the conduction band of nanoporous TiO2 electrode, which is below the dye's excited state and where the TiO2 absorbs a small percentage of the solar photons from the UV region. The dye oxidizes as a result.

$S^+/S + h\nu \rightarrow S^+/S^*$

$S^+/S^* \rightarrow S^+/S + e^- (TiO_2)$

3. These injected electrons are transported between TiO_2 nanoparticles and diffuse towards the back contact (transparent conducting oxide [TCO]). Through the external circuit, electrons reach the counter electrode.
4. The electrons at the counter electrode reduce $I^-{}_3$ to I^-; thus, dye regeneration or the regeneration of the ground state of the dye takes place due to the acceptance of electrons from I− ion redox mediator, and I− gets oxidized to I^{-3} (oxidized state).

$S^+/S^* + e^- \rightarrow S^+/S$

5. Again, the oxidized mediator ($I^-{}_3$) diffuses towards the counter electrode and reduces to I ion.[23]
$I^-{}_3 + 2e^- \rightarrow 3I^-$

TiO_2 is the most preferred choice for semiconductors in DSSCs because of its unique chemical and physical characteristics.
First, TiO2's conduction band edge is slightly lower than the excited state energy level of many sensitized dyes, which is a need for effective electron injection.
Second, TiO2 has a high dielectric constant (e = 80 for anatase) that allows the injected electrons to be effectively electrostatically shielded from the oxidized dye molecules adsorbed on the TiO2 surface, preventing recombination before regeneration of the dyes by the redox electrolyte. The comparatively high refractive index of TiO2 (n = 2.5 for anatase) allows for effective diffusive light scattering inside the nanoporous film, enhancing light harvesting potential substantially. Furthermore, TiO2 is stable under a wide variety of conditions, including high acidity and high temperature.
Lastly, TiO2 is inexpensive, abundant, and nontoxic. [16,24]
Considerable research and efforts have been concentrated on designing, manufacturing, and modifying multifunctional TiO2 photoanodes during the past few decades.[24]

3.3.2 Quantum Dots (Q-Dots)

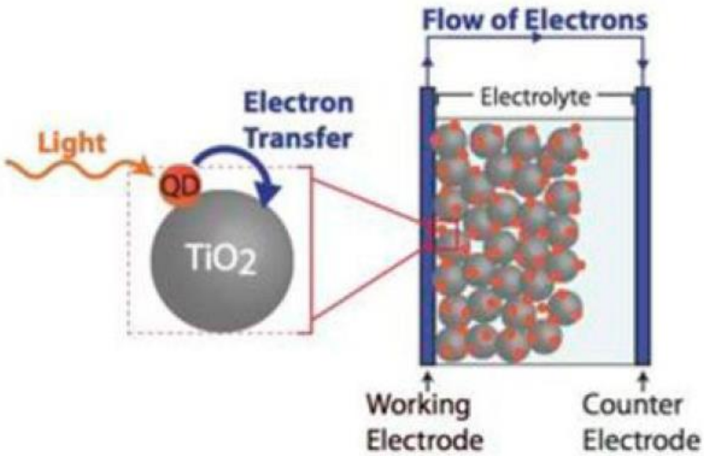

Fig-4: Typical Schematic of a QDSSC (Quantum dot sensitized solar cell). Light interacts with the QD, which causes electrons to be injected into TiO2 and drawn off an external circuit to generate electricity. The electrolyte then replenishes the charge carriers

The energetics of quantum dots can be varied by changing their particle size. Q-dots with higher band energy can be used to promote [25,26], rectify [27], or suppress [28,29] electron transfer between two semiconductor nanostructures. Such composite structures rectify the flow of charge carriers and improve the photocatalytic performance of nanostructure semiconductor-based systems. [25]
The band gaps can be precisely adjusted using quantum dots to convert longer-wave light and therefore enhance the efficiency of solar cells. [7]
Semiconductor quantum dots (QDs) such as PbSe, InAs, CdSe and PbS, with their tunable band edge, offer new opportunities for harvesting light energy in the visible region of the solar spectrum.[29]
Under visible light irradiation, a mixture of PPV and CdSe quantum dots promote charge separation and photocurrent production.
Quantum dots can generate multiple charge carriers with a single high energized photon. Multiple carrier generation in PbSe nanocrystals has shown that a single photon with an energy higher than the bandgap can create two or more excitons [30,31].
Quantum Dots can be used to make hot carrier cells. Usually, a photon's extra energy is wasted as heat. However, in hot carrier cells, the extra energy from the photons results in higher-energy electrons, which leads to a greater voltage. [32,33]

TiO_2 with CdSe nanoparticles

The binding of CdSe quantum dots to TiO2 is facilitated by bifunctional linker molecules (HOOC-R-SH) containing carboxylate and thiol functional groups. TiO2 nanoparticles have been effectively linked to CdS and gold nanoparticles using this method.

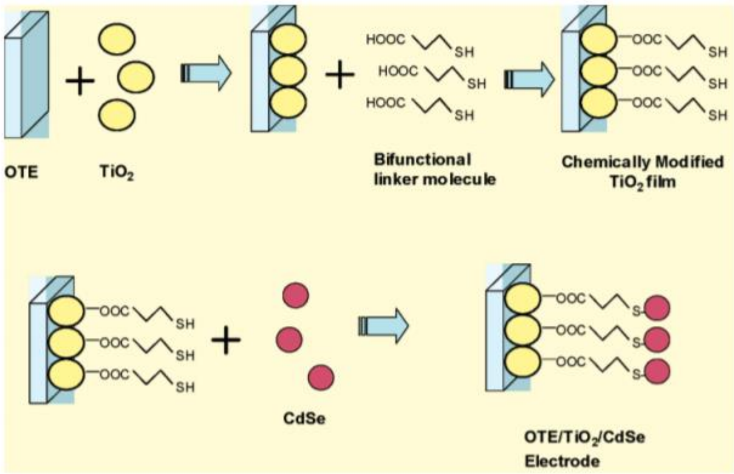

Fig-5: Linking CdSe QDs to TiO2 surface with a bifunctional surface modifier.

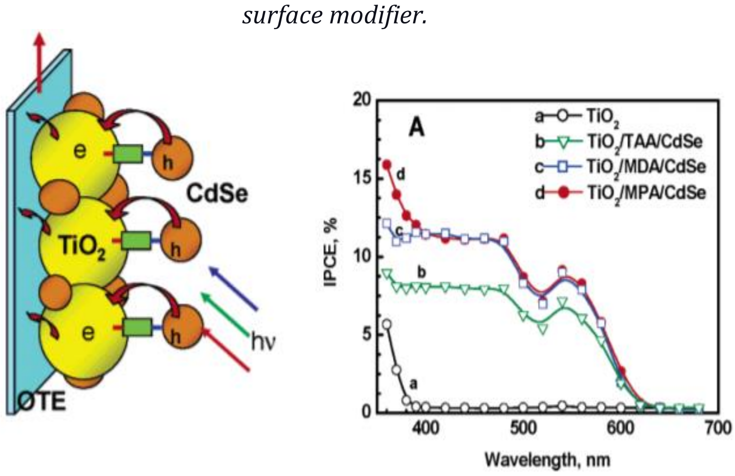

Fig-6:. Photoresponse of the TiO2 film before and after modification with CdSe quantum dots

The graph shows the increase in IPCE% (The incident photon to current conversion efficiency) with CdSe quantum dots. Hence, the photoelectrochemical behavior of a CdSe quantum dot-based solar cell shows that semiconductor nanocrystals can be used to capture light energy.[25]

Quantum dot solar cells are still in the early stages of development. III/V semiconductors and other material combinations such as Si/Ge or Si/Be Te/Se are explored as material systems for QD solar cells.
Potential advantages of these Si/Ge QDs are that they allow higher light absorption, particularly in the infrared spectral region. Furthermore, there is a potential of an increase in the photocurrent at higher temperatures, and improved radiation hardness compared to conventional solar cells.

3.3.3 Carbon Nanostructures

Many researchers have turned to carbon nanostructures like single-wall carbon nanotubes (SWCNT) assemblies for energy conversion devices because of their unique electrical and electronic characteristics, wide electrochemical stability window, and large surface area.

Carbon nanotube composites in the photoactive layer

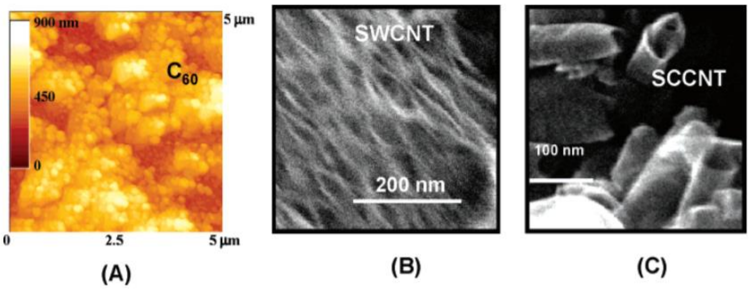

Fig-7: Carbon nanostructured films cast on conducting glass electrodes A)AFM image of C60 cluster film; B)Single Wall Carbon Nanotube; C) Stacked cup carbon Nanotube

Fullerenes can act as an electron shuttle in photo-chemical solar cells.[34]
Fullerene clusters, SWCNTs, and SCCNTs (stacked cup carbon nanotubes) can be conveniently deposited as thin films on optically transparent glass electrodes. The clusters of fullerenes or nanotubes suspended in a nonpolar solvent are readily driven to an electrode surface by the application of an electric field. The SWCNT films cast on optically transparent electrodes respond to visible light excitation. When used in a photoelectrochemical cell containing I_3^- /I- as a redox couple, these electrodes exhibit photocurrent generation.
There is low photocurrent generation efficiency in SWCNT films which is attributed to ultrafast recombination of photogenerated charge carriers. SCCNT films, on the other hand, exhibit relatively high IPCE.

Carbon nanotubes as a transparent electrode

Carbon nanotubes are also frequently used as electrode materials in photovoltaic devices (widely implemented in the short-term solution) [35,36]. Carbon nanotube films are most often made by growing them directly, using carbon vapour deposition techniques (CVD), or by coating carbon nanotube solutions [30]. Carbon nanotube films have been extensively studied both in the OTE (i.e., working electrode) and in the counter-electrode in dye-sensitized and organic solar cells [37]. Their initial advantages are in their structural strength, cost, and flexibility, allowing for flexible polymer or liquid phase photovoltaic devices [38].
Carbon nanotubes have the potential to significantly lower the costs in thin-film solar cell devices because the vacuum deposition processes of conventional OTE materials are expensive, and the costs of indium and platinum (the most common counter-electrodes) are high.[36]

4. PLASTIC SOLAR CELL - COST EFFECTIVE SOLAR CELL

Chemists at the University of California, Berkeley, have developed a technique for producing low-cost plastic solar cells that can be painted on nearly any surface. Only 1.7 percent efficiency is achieved yet by the new plastic solar cells.
"Our efficiency is not good enough yet by about a factor of 10, but this technology has the potential to do a lot better," said A. Paul Alivisatos, professor of chemistry at UC Berkeley and a member of the Materials Science Division of Lawrence Berkeley National Laboratory. "There is a pretty clear path for us to take to make this perform much better."

Nanorods function like wires because they create electrons when they absorb light of a certain wavelength. These electrons flow through the nanorods until they reach the aluminium electrode, where they combine to produce a current, which is then used to generate energy. This type of cell is cheaper to manufacture than conventional ones for two main reasons. To begin with, these plastic cells are not composed of silicon, which can be quite costly. Second, unlike traditional silicon-based solar cells, these cells do not require expensive equipment such as clean rooms or vacuum chambers to manufacture.[39]

5. CONCLUSIONS

As traditional power generating technologies such as fossil fuels and nuclear power come under more scrutiny, solar power is becoming increasingly appealing. The amount of power that could be gathered from sunlight is still beyond our requirements. However, because of the high manufacturing costs associated with solar panels, as well as their low efficiency, it takes a long time to recoup the investment, whether placing solar panels on a home's roof or constructing a megawatt-scale solar farm.
Manufacturing the nanomaterials that might overcome the present constraints on PV efficiency is still a challenge. However, it's encouraging to see extensive research being done in this field and some small businesses starting to market nano-enhanced solar panels. Solar power is projected to break out of its current niche markets and capture a significant part of the global energy industry at its current rate of growth.

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