

MODERN THIRD GENERATION SOLAR PHOTOVOLTAIC TECHNOLOGY: DYE SENSITIZED SOLAR CELL

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Abstract: Depleting conventional energy resources are forcing the world to search for new and renewable energy resources. Solar energy is one of the potent and abundant energy resource. To use the solar energy to its fullest along with conventional technology has specific limitations. These limitations can be eliminated by use of Dye Sensitized Solar Cell (DSSC). DSSC can be seen as promising future technology. It is advantageous over Silicon (Si) based Photovoltaic (PV) cell in terms cost, easy manufacturing, stability at higher temperature, aesthetics, etc. Also it works in indoor conditions i.e. diffused sunlight which nearly not feasible with conventional PV cells. Now Research and Development Departments of many countries like Japan, Germany, USA, Switzerland, India, China and many firms like G-Cell, Oxford PV, Sony, TATA-Dycesol are working on DSSC to improve its various aspects so as to make it more applicable in various conditions. The paper will discuss the concept, construction, working of DSSC. Also it will illustrate current applications of DSSC.

Keywords: photovoltaic, Dye Sensitized Solar Cell (DSSC), Silicon (Si) based Photovoltaic (PV) cell, solar energy.

1. INTRODUCTION

The earth receives more energy from the sun in just one hour than the world's population uses in a whole year. The total solar energy flux intercepted by the earth on any particular day is 4.2×10^{18} Watt hours or 1.5×10^{22} Joules. This is equivalent to burning 360 billion tons of oil per day. In fact the world's total energy consumption of all forms in the year 2000 was only 4.24×10^{20} . With about 37.1 GW of solar PV power installed in 2013, world solar PV power capacity increased about 35% to 136.697 GW. In solar power, Germany is leading country in the world with approximately 40 GW installed capacity almost half of its total power requirement, Italy 19 GW, China 10 GW and Japan 5.5 GW. The world's largest fossil fuel producer Saudi Arab is also having ambitious plan of 41 GW of solar power by 2032 and UK 22 GW by 2020 [1]. It is known that India is a rarest of the countries rich with sunlight radiation and offers the best hope to revolutionize solar energy in

the world. It receives about 5000 trillion kWh of radiation per year. For every square kilometre 50 MW of solar power can be commissioned that can yield average annually 42.5

GWh of electricity assuming present PV cell efficiency of 15%. India's current power requirement is 1102900 GWh as per Central electricity authority. This means an area of 26000 sq. Km is required to meet countries annual electricity demand using solar energy. The area is meagrely 0.82%. Such is the gravity of sunlight which India receives. Presently the country has more than 2500 MW of grid connected power plants and additional 200 MW of off grid systems. The national solar mission targets 20000 MW grid connected solar power and additional 2000 MW of grid solar by the year 2022 [2].

2. THIRD GENERATION SOLAR CELLS

Currently there is a lot of solar research going on in what is being referred to in the industry as Third-generation solar cells. In fact according to the

number of patents filed last year in the United States solar research ranks second only to research in the area of fuel cells. This new generation of solar cells is being made from variety of new materials besides silicon, including nano-tube, silicon wires, and solar inks using conventional printing press technologies, organic dyes, and conductive plastics. The goal of course is to improve on the solar cells already commercially available by making solar energy more efficient over a wider band of solar energy (e.g., including infrared), less expensive so it can be used by more and more people, and to develop more and different uses. Currently, most of the work on third generation solar cells is being developed by new companies and for the most part is not commercially available [3].

3. DYE SENSITIZED SOLAR CELL (DSSC)

3.1. Introduction to DSSC

Michael Grätzel and Brian O'Regan invented "Dye-sensitized solar cells", also called "Grätzel cells", in 1991. A dye-sensitized solar cell (DSSC) is a low-cost solar cell belonging to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photo electrochemical system. The modern version of a dye solar cell, also known as the Grätzel cell, was originally co-invented in 1988 by Brian O'Regan and Michael Grätzel at UC Berkeley and this work was later developed by the aforementioned scientists at the École Polytechnique Fédérale de Lausanne until the publication of the first high efficiency DSSC in 1991. Michael Grätzel has been awarded the 2010 Millennium Technology.

3.2. Principle

Figure in the below illustrates the operation principal of DSSC. In DSSC, the separation of

electron-hole pair occurs on the surface of nano particle semiconductor oxide electrode chemically absorbed with dye molecules. The sunlight is absorbed to generate electron succession from dye molecule's HOMO (Highest Occupied Molecular Orbital) energy level to LUMO (Lowest Unoccupied Molecular Orbital) and this electron is injected to the semiconductor oxide's conduction band. Here, the electron injection occurs at a fast pace of femto second to pico second and the oxidized dye is regenerated within several nano seconds. On the other hand, the recombination or back reaction, of which the electron undergoes the surface state to be lost as electrolyte or absorbed dye molecule, occurs somewhat slow that most photoelectrons are injected to the semiconductor's conduction band to participate in electron delivery and, hence, to promote the photoelectric energy conversion efficiency. The injected electron moves to the conductive film through inter phase between particles of oxide electrode and creates electric current. Here, dye molecule's HOMO is reduced by the electrolyte to complete the operation process of solar cell. Unlike the semiconductor junction type, the DSSC is a photoelectric chemical type of solid/liquid junction. It especially includes oxidation-reduction electrolyte that is expressed differently from the ideal semiconductor junction diode based equation:

$$V_{oc} = \frac{KT}{c} \ln \left(\frac{I_{inj}}{n_{so} KET[OX]} \right), \quad (1)$$

$$I - 3 + 2Ccb(TiO_2) \xrightarrow{Kgt} \rightarrow 3I. \quad (2)$$

The observed I_{ph} photoelectric current is determined by the I_{inj} electric current which subtracts I_r , the electric current lost by surface recombination. In other words, $I_{ph} = I_{inj} - I_r$ and the open-circuit voltage is expressed in equation (1).

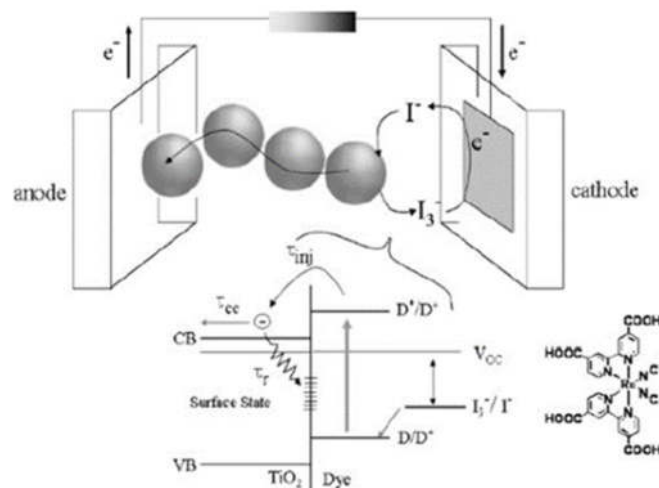


Fig. 1. Operation Principle of DSSC

Here, n_{so} is the concentration of electron on TiO_2 surface and k_{ET} corresponds to speed constant equation (2) which combines the electron injected to TiO_2 with electrolyte's oxidation (or I_3^-). The voltage decrease can be prevented when the speed of reduction from I_3^- to I^- is slow. The recombination process passing through technology to regulate the nano particle's surface state which is closely related to the energy conversion efficiency.

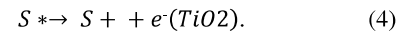
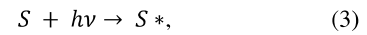
3.3. Construction

In the case of the original Grätzel and O'Regan design, the cell has 3 primary parts. On top is a transparent anode made of fluoride-doped tin dioxide ($SnO_2:F$) deposited on the back of a typically glass plate. On the back of this conductive plate is a thin layer of titanium dioxide (TiO_2), which forms into a highly porous structure with an extremely high surface area. TiO_2 only absorbs a small fraction of the solar photons (those in the UV). The plate is then immersed in a mixture of a photosensitive ruthenium-polypyridine dye (also called molecular sensitizers) and a solvent. After soaking the film in the dye solution, a thin layer of the dye is left covalently bonded to the surface of the TiO_2 . A separate plate is then made with a thin layer of the iodide electrolyte spread over a conductive sheet, typically platinum metal. The two plates are then joined and sealed together to prevent the electrolyte from leaking. The construction is simple enough that there are hobby kits available to hand-construct them. Although they use a number of "advanced" materials, these are inexpensive compared to the silicon needed for normal cells because they require no expensive manufacturing steps. TiO_2 , for instance, is already widely used as a paint base. One of the efficient DSSCs devices uses ruthenium-based molecular dye, e.g. $[Ru(4,4\text{-dicarboxy-}2,2\text{-bipyridine})_2(NCS)_2]^{3+}$, that is bound to a photo-anode via carboxylate moieties. The photoanode consists of 12 μm thick film of transparent 10–20 nm diameter TiO_2 nanoparticles covered with a 4 μm thick film of much larger (400 nm diameter) particles that scatter photons back into the transparent film. Then on this a liquid electrolyte is applied which is typically I_3^- [6].

3.4. Working

The following primary steps convert photons to current:

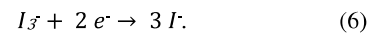
1. The incident photon is absorbed by Ru complex photosensitizers adsorbed on the TiO_2 surface.
2. The photosensitizers are excited from the ground state (S) to the excited state (S^*). The excited electrons are injected into the conduction band of the TiO_2 electrode. This results in the oxidation of the photosensitized (S^+):



3. The injected electrons in the conduction band of TiO_2 are transported between TiO_2 nanoparticles with diffusion toward the back contact (TCO). And the electrons finally reach the counter electrode through the circuit.
4. The oxidized photosensitizer (S^+) accepts electrons from the I^- ion redox mediator leading to regeneration of the ground state (S), and the I^- is oxidized to the oxidized state, (I_3^-):



5. The oxidized redox mediator, I_3^- , diffuses toward the counter electrode and then it is reduced to I^- ions. The efficiency of a DSSC depends on four energy levels of the component: the excited state (approximately LUMO) and the ground state (HOMO) of the photosensitizer, the Fermi level of the TiO_2 electrode and the redox potential of the mediator (I^-/I_3^-) in the electrolyte [7]:



4. PROBLEMS WITH CONVENTIONAL PV CELL

1. The n-type layer has to be fairly thick. This also increases the chance that a freshly ejected electron will meet up with a previously created hole in the material before reaching the p-n junction. These effects produce an upper limit on the efficiency of silicon solar cells.
2. Solar cells require a relatively thick layer of doped silicon in order to have reasonable photon capture rates; however silicon processing in terms of growing crystal is expensive. Thus overall cost increases.
3. Purity of Si plays a very important role in efficiency.
4. Most of solar energy is not converted into electricity but absorbed as heat by PV cell. In general a PV cell absorbs more than 80% of incident energy as heat in the cell. Hence temperature of cell increases.
5. At elevated temperatures the efficiency of PV cell is affected adversely. Solar Si PV are incapable to convert in diffused sunlight into electricity. So operation of Si PV is nearly impossible in indoor and cloudy conditions.
6. Though PV panels have no considerable maintenance or operating costs, they are fragile and can be damaged relatively easily.

5. ADVANTAGES OVER CONVENTIONAL PV CELL

1. Due to separate and favourable kinetics of electron ejection, collection, transportation theoretically there is no bar or efficiency.
2. DSSCs use low-cost materials; are simple to manufacture, and are technically attractive.
3. DSSC cell manufactured by using Role To Role Printing technology. That means all the manufacturing processes are done at single work station with faster rate and final DSSC role is produced. This is very cost effective method.
4. Components of DSSC are easily available and there is no requirement of materials with stringent specifications.
5. DSSCs are normally built with only a thin layer of conductive plastic on the front layer, allowing them to radiate away heat much easier without raising temperature of cell, and therefore operate at lower internal temperature.
6. At elevated temperature working is not affected as efficiency improves with temperature. As a result of these favourable "differential kinetics" (the reaction rate), DSSCs work even in low-light conditions, allowing them to work under cloudy skies and non-direct sunlight when traditional designs would suffer a "cut out".
7. DSSCs can be replacements for existing technologies in "low density" applications like rooftop solar collectors, where mechanical reliability and light weight of the glass-less collector are important factors [8].

6. CASE STUDY

Basically manufacturing of DSSC is very difficult when it comes to mass production. Also various issues related to DSSC are currently in research phase. The firms involved in manufacturing of DSSC are:

- G-Cell,
- Oxford,
- Dyesol.

Out of this only G-Cell is producing DSSC commercially on mass production basis.

6.1. G-Cell

1. The Solar Powered Keyboard Folio for iPad Air 2 & iPad Air allows users to type with an iPad from the home, the office or on a daily commute without the need to change batteries or revert to a mains powered charger. The total cost in UK is £79.9 (5014 INR).
2. The Graetzel solar backpack is a collectable all-weather bag that is durable, rugged and lightweight. This innovative design includes a Dye Sensitized Solar Cell (DSSC) that will power your mobile phone, GPS, iPod or small electronic device. The solar cell harvests energy from the sun

and stores it in the Power Bank battery (provided) for continuous access to power. DSSC Specification: Power (P_{max}) 0.5 W minimum Operating Current (I_{mp}) 100 mA typical Operating Voltage (V_{mp}) 5.5 V typical (Solar specification @ 1000 W/m²) £60.00 (4238 INR).

3. G-Cell sample DSSC module – 1/2 watt module, 200 mm x 150 mm active aperture Power (P_{max}) 0.5 W minimum Operating Current (I_{mp}) 100 mA typical Operating Voltage (V_{mp}) 5.5 V typical (Solar specification @ 1000 W/m²). Its cost is £50.00 (3529 INR) [10].

6.2. Dyesol

Founded in 2004 engages in the commercialization of DSSC. Dyesol has developed a complete range of equipment for production and testing of DSSC devices which ensure optimum performance and reproducibility. The equipment can be utilized for both rigid and semi-flexible substrates, and is available for manual or semi-automatic operation. We provide proven training procedures, simple and straightforward process instructions, quality & testing procedures, and easy-to-use equipment manuals. [11] Talking on cost it is estimated materials costs for relatively small-scale DSC module production (7MW_p p.a.): 70US\$/m² corresponds to 1\$/W_p at 7% module efficiency [14].

6.3. Oxford PV

Oxford PV is developing a solid state solar cell which is optimized to drive a paradigm shift in the aesthetics, performance and cost of Building Integrated Photovoltaic (BIPV) systems. [12] Oxford PV in 2011 spun out from the University of Oxford by Isis Innovation Ltd., has developed a dye-sensitized solar cell (DSSC) technology that is manufactured from cheap, abundant, non-toxic and non-corrosive materials and can be scaled to any volume. The solar cells are printed onto glass or other surfaces, are available in a range of colors and could be ideal for new buildings where solar cells are incorporated into glazing panels and walls. Going beyond liquid electrolyte, Oxford PV has implemented solid organic electrolyte, enabling entire solar modules to be screen printed onto glass or other surfaces [13]. The materials used are plentiful, environmentally benign and very low cost.

7. CONCLUSION

Companies like Oxford-PV, Dyesol are well established in this area of the industry. However, there are problems that prevent the mass production and wide use of DSSC technology. DSSCs are still in the early stages of the development cycle. Efficiency gains are possible and more widespread studies are underway. These include the use of quantum dots (small particles of semi-conductor materials) for

conversion of higher-energy (higher frequency) light into multiple electrons and changing the doping of the TiO₂ to better match it with the electrolyte being used. Replacing the liquid electrolyte with a solid is an ongoing area of research. Recent experiments using solidified melted salts have shown some promise, but currently suffer from higher degradation during continued operation, and are not flexible.

Overall, DSSC technology may not be attractive for large-scale deployments where higher-efficiency cells are more viable, although more expensive. But, even small increases in the DSSC conversion efficiency may make them suitable for some of these roles.

The dye sensitized solar cell is a brilliant idea because it applies different mechanisms and has many advantages compare with traditional semiconductor solar cell. Though it is far from mature, DSSCs technology will be an important renewable energy source in future if some technology breakthroughs are made. It may be possible to use mixed dye to overcome the band absorption limits of each dye to improve the overall efficiency.

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Biographical note



Chiranjeev Banne received his B.E degree mechanical engineering from Shivaji University, Kolhapur, India in 2016. Since 2016 he has been a working professional as a mechanical design engineer in the field of Automotive Sector. Currently he is working at Brose India Automotive Systems Pvt. Ltd. Previously he was associated with Tata Technologies. His area of interest are design, Plastic and renewable energy.

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