12-2021

Flexible Quantum Dot Solar Cell with Nanostructure Titanium Dioxide Photoanode with Modified Counter Electrode

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FLEXIBLE QUANTUM DOT SOLAR CELL WITH NANOSTRUCTURE TITANIUM DIOXIDE PHOTOANODE WITH MODIFIED COUNTER ELECTRODE

A Thesis

by

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Submitted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE

Major Subject: Chemistry

The University of Texas Rio Grande Valley

December 2021

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December 2021

ABSTRACT

Majumder, Haimanti, Flexible Quantum Dot Solar Cell with nanostructure TiO_2 photoanode with modified counter electrode. Master of Science (MS), December, 2021, 43 pp, 1 table, 20 figures, references, 108 titles.

Because of unique photovoltaic properties, nanostructured morphologies of TiO_2 on flexible substrate have been studied widely in the recent years in dye sensitized solar cells (DSSCs). Nanostructured electrode materials with high surface area can promote rapid charge transport and thus improve the light-to-current conversion efficiency. Herein, this project generates an improved photoanode with forest like photoactive TiO_2 hierarchical microstructure using a simple and facile hydrothermal route. To improve the photocurrent efficiency, PbS quantum dot has been applied in different thickness to evaluate best performance. The deposition of quantum dot was done by easy SILAR cycle. Four different SILAR cycle has been done to perform the chemical deposition on the TiO_2 substrate. Instead of Pt based counter electrode, a modified carbon fiber based counter electrode has been used in this experiment. QDSSC with TiO_2 nanostructured flexible photoanode showed a significant energy conversion efficiency to a certain thickness of quantum dot.

DEDICATION

I dedicate my work to late parents Prova Majumder and Tapas Majumder and my late grandmother Sadhana Majumder. There is no single moment when I do not miss them. One day we will all meet again.

ACKNOWLEDGMENT

At first, I would like to express gratitude to my advisor Dr. M Jasim Uddin for the continuous help throughout my journey here at UTRGV. I would like to express my gratefulness towards Dr. Chen Lin for helping me throughout my thesis works. Then I would like to thank all my lab members for their support and cooperation. I would like to thank my partner Muhtasim Ul Karim Sadaf, without whom nothing was ever possible. I would like to thank my friends Prince, Prosanto, Panda, Julia, Zaida, Najla, Ulises, Javier, Rigo, Micheal, Ishrat, Lubna, Maliha. After everything, nothing was possible without family specially my late grandmother, my aunt and my brothers.

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CHAPTER I

INTRODUCTION

Over the past decade, numerous efforts to find better ways to generate renewable, low cost, and easy to manufacture energy remains a pressing matter for scientists to address as the demand of energy increases day after day[1]. The extraction and usage of fossil fuel is a major cause of environmental pollution by emitting greenhouse gases into the atmosphere which increase the earth's temperature, already creating irreparable calamity which severely affects human health [2,3]. The rapid increase of world populations and urbanization has increased energy demand for electronic needs in this technologically advancing world and grinding the industry to a halt would only cause more damage, meaning that altering the industry is the better option[4].

From the figure 1 given below, it is noticed that petroleum is used almost 35% of total energy consumption which is a major portion. Petroleum is mainly used for transportation purpose. Another big consumption is natural gas which is 34%. The percentage of coal and nuclear electric power is slightly less than renewable energy which is 12%.

The term "renewable energy" is energy derived from a broad spectrum of resources, all of which are based on self-renewing energy sources such as sunlight, wind, flowing water, the earth's internal heat, and biomass such as energy crops, agricultural and industrial waste, and municipal waste[5].

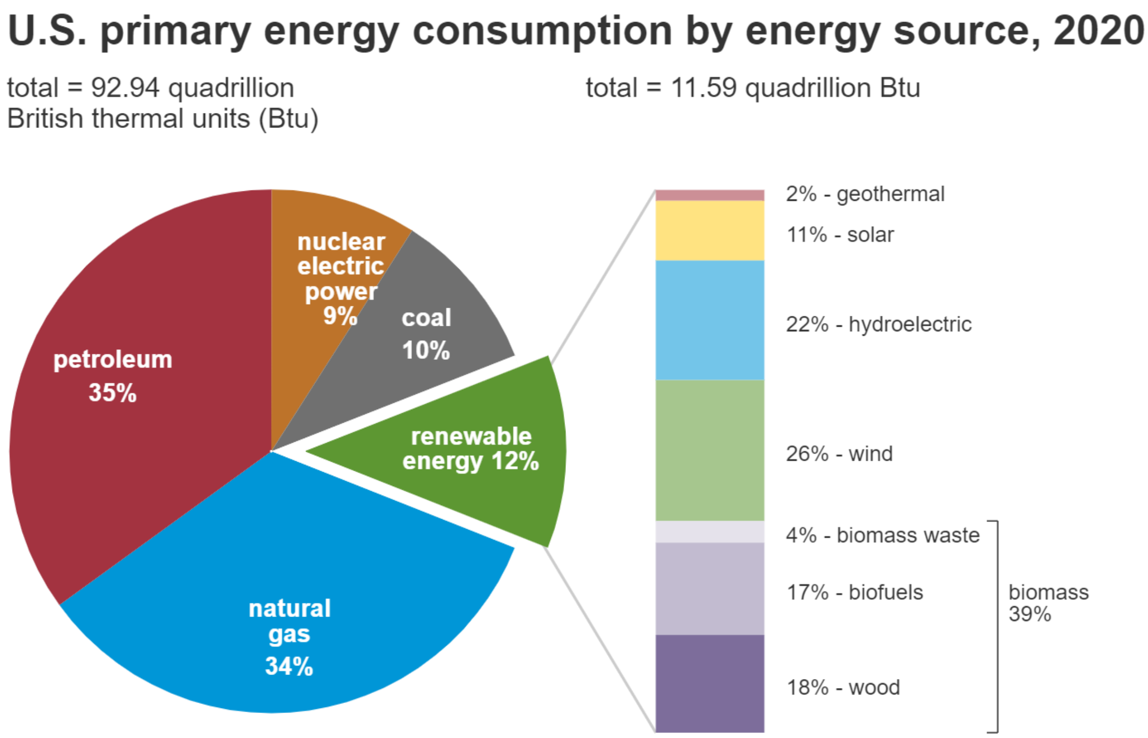

Figure 1: U.S. primary energy consumption by energy source, 2020 [6]

With the increasing amount of energy consumption there has been an adequate amount of energy generation to keep up the balance. Among all the sources of power, sun is also a great source of power. Solar energy is abundantly available across the earth with no combustion or harmful waste being produced in the process of harnessing, converting, and generating power; it's clean and better yet: cheap[7]. Solar energy attributes the potential to fulfill the energy demands of the entire world if technologies for its harvesting and supplying were readily available.[8] The sun is the source of energy in the solar system; therefore, it would be more convenient to find a way to harness solar energy to its greatest extent, namely using photovoltaic cells. At the time however, it is still challenging to achieve high photocatalytic and photoelectrochemical performances through solar light [9]. Though solar energy has great performance still contribution of solar energy to the global energy supply is still negligible[10].

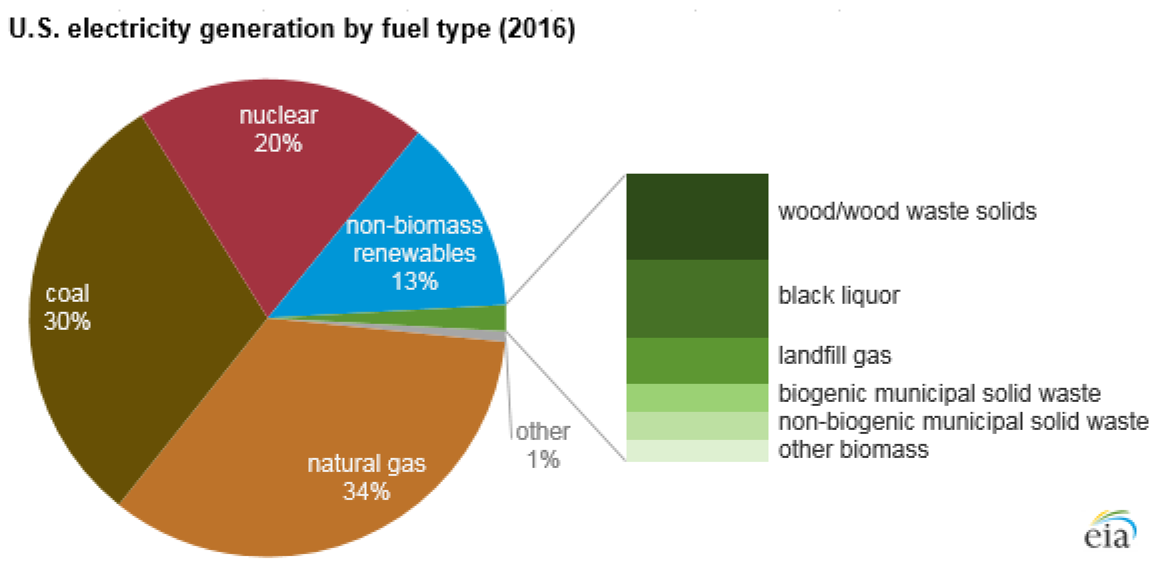

Figure 2: Energy generation by fuel type [11]

The main solar energy concept is the harvesting and utilization of light and/or heat energy generated by the Sun and technologies (passive and active) involved in achieving such goals. [12].

A classification of solar energy is shown in the figure 3. Basically, passive technology involves the accumulation of solar energy without transforming thermal or light energy into any other form [13]. If we consider the active solar energy technologies, we get to know more about photovoltaic technology.

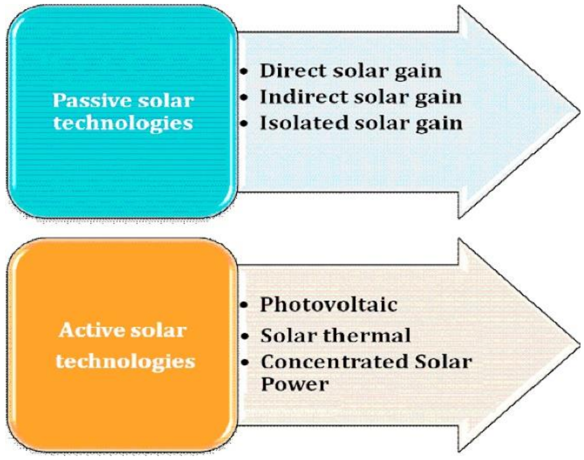

Figure 3: Classification of solar technology [14]

Photovoltaic (PV) cells are designed to directly transform sunlight into electricity, with their small size being convenient for smaller-scale tasks [15]. PV Cells are one of the most promising methods to achieve the goal of plentiful efficient energy by harnessing and utilizing sunlight to drive the internal chemical reactions that create electricity. Photovoltaic cell is a growing power source which has started from a very small quantity of use of household usage. As the time passed, the usage of photovoltaic sources has been increasing every year. As figure 4, the usage of photovoltaic energy has increased a lot.

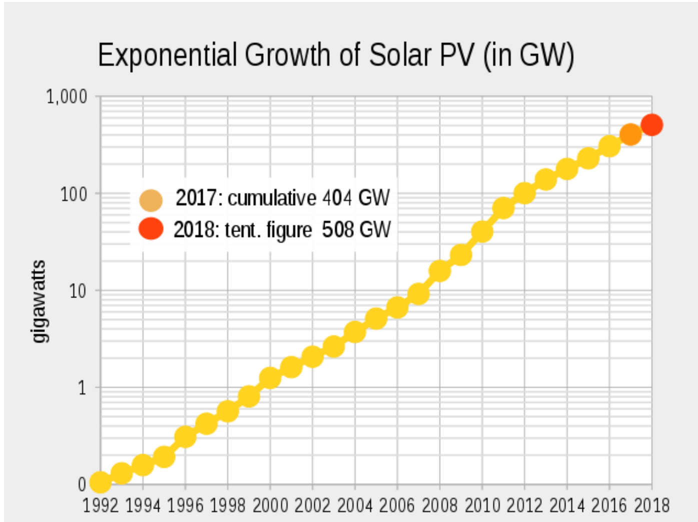

Figure 4: growth of photovoltaic [16]

The main types of photovoltaic cells currently being manufactured and experimented on are Dye-Sensitized solar cells (DSSCs), which garner interest from research and industrial applications both for their potential low-cost, environmentally friendly, easy-to-manufacture, and relatively high photo-conversion efficiency properties [17].

DSSCs typically consist of a nanocrystalline, in some cases a TiO_2 film, covered by a monolayer of molecular dye, known as the sensitizer which absorbs photons and uses the energy of its own excited electrons to excite electrons to the TiO_2 semiconductor, electrolytes, and/or counter electrodes with a photoanode material that transports the injected electrons from the excited dye molecules to the external circuit and supports the sensitizer. Changing the morphology of TiO_2 photoanodes to achieve high performance can be done by enhancing properties such as surface area, electron transport, electron-hole recombination rate and light harvesting features. With the increasing popularity of wearable electronic devices, numerous efforts have integrated photovoltaic cells into fibers[18]. Other benefits of DSSCs include their aesthetic appeal due to their partial transparency and color, easy integration into building architecture and short energy payback

time, which is the time required to generate such quantity of energy equal to the energy embodied within the system during production [19]. The efficiency of conversion of the cell is not up to the best thin-film cells. However, theoretically, the price/performance ratio should be such that it high and have capability to compete with other forms of electrical energy generation by achieving grid parity [20].

A traditional DSSC is mainly composed of three parts, including a dye-sensitized nanocrystalline porous semiconductor photoanode, electrolyte and a Pt counter electrode. Although platinum can meet the main requirements of counter electrode material for DSSCs due to its high catalytic activity and good electrical conductivity, however, the high cost, limited reserve and the possibility of corrosion by I3 −/I− redox electrolyte of Pt confine its application to a large scale. Therefore, exploring non-platinum counter electrode material with low cost and high catalytic activity has important practical significance for large-scale application of DSSC [21,22].

Quantum dot-sensitized solar cells (QDSSCs) have gained attention because of their simple fabrication process, low cost, and excellent photovoltaic performance, along with their excellent optoelectronic properties such as ability of multiple exciton generation with absorption of single photon, high absorption coefficients, large intrinsic dipole moments and tunable energy gap by quantum confinement effect [23,24,25,26,27,28]

CHAPTER II

LITERATURE REVIEW

Fundamental of solar cell

Solar cell works following the principle of photovoltaic effect. The photovoltaic effect is the generation of voltage and electric current in a material upon exposure to light. It is a physical and chemical phenomenon.[29] The conversion occurs basically by absorbing light and ionizing crystalline atoms and creating a free, creating positively charged ions and negatively charged electrons. Solar cell is a photoelectric cell or a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light.

Solar cell can be designed to be worked as a photovoltaic in both direct sunlight and artificial sunlight. The operation of photovoltaic cell generally requires three basic attributes. [30]

1. The absorption of light which generally generates the electron-hole pairs
2. The separation of charge carriers of opposite types
3. The separate extraction of those carriers to an external circuit.

In figure 5, a conventional photovoltaic cell structure is depicted. Sunlight is incident from the top, on the front of the photovoltaic cell. A metallic grid forms one of the electrical contacts of the diode and allows light to fall on the semiconductor between the grid lines and thus be absorbed and converted into electrical energy. An antireflective layer between the grid lines increases the amount of light transmitted to the semiconductor. The semiconductor diode is fashioned when an

n-type semiconductor and a p-type semiconductor are brought together to form a metallurgical junction. This is typically achieved through diffusion or implantation of specific impurities or via a deposition process. The diode's other electrical contact is formed by a metallic layer on the back of the solar cell.[31]

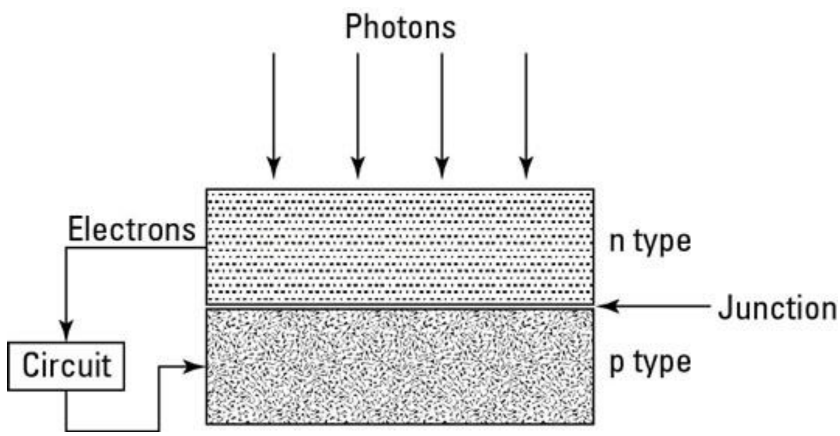

Figure 5: working procedure of photovoltaic cell converting sunlight to energy [32]

The comprehension of p-n junction solar cell gives an idea of improving the efficiency of solar cell, manufacturing cost, consuming energy for the fabrication. Also, the band gap of the material used in the manufacturing of a solar cell gives important information too. The electrons of an isolated atom has a discrete energy levels. When atoms approach to form crystals, the energy levels spit into separate but closely spaced levels because of atomic interactions, which result in a continuous energy band. Between these two bands, the lower one is valence band and the upper one is called the conduction band. There is an energy gap between this bands, which is called band gap and it is denoted as E_g. [33]

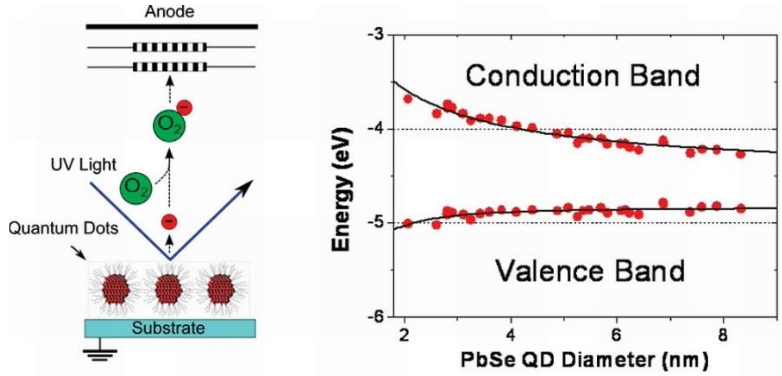

Figure 6: example of valence band and conduction band of QD material.[34]

Photovoltaic Characterization Parameters

The photovoltaic parameters that are used to characterize the performance of a solar cell are: short circuit current density J_{SC}, open circuit voltage V_{OC}, fill factor (FF) and power conversion efficiency (η), J_{SC}, V_{OC}, FF are determined from the J-V characteristics curve, however, fill factor can also be calculated the Jsc and Voc values. The power conversion efficiency can be determined from these three parameters. These parameters are very important in solar cell characterization as they determine how efficient the cell, they can be optimized for designing efficient solar cell.

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). To remove the dependence of the solar cell area, it is more common to list the short-circuit current density (Jsc in mA/cm^2) rather than the short-circuit current. [35]

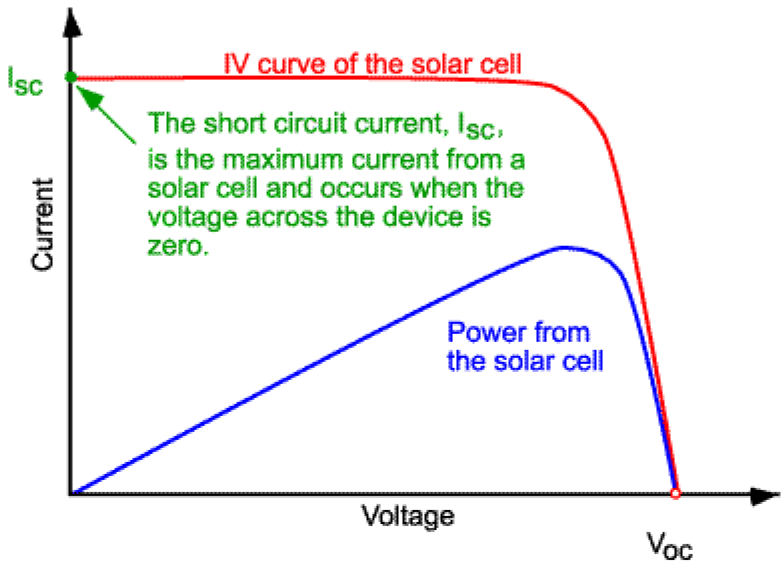

Figure 7: A figure of short circuit current and open circuit voltage[35]

The open-circuit voltage, Voc, is the maximum voltage available from a solar cell which occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light generated current.[35] Open circuit voltage can also be calculated by the equation[36]

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{J_{ph}}{J_0} + 1\right) \approx \frac{k_B T}{q} \ln\left(\frac{J_{ph}}{J_0}\right),$$

The "fill factor" (FF) is the parameter which, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of Voc and Jsc.

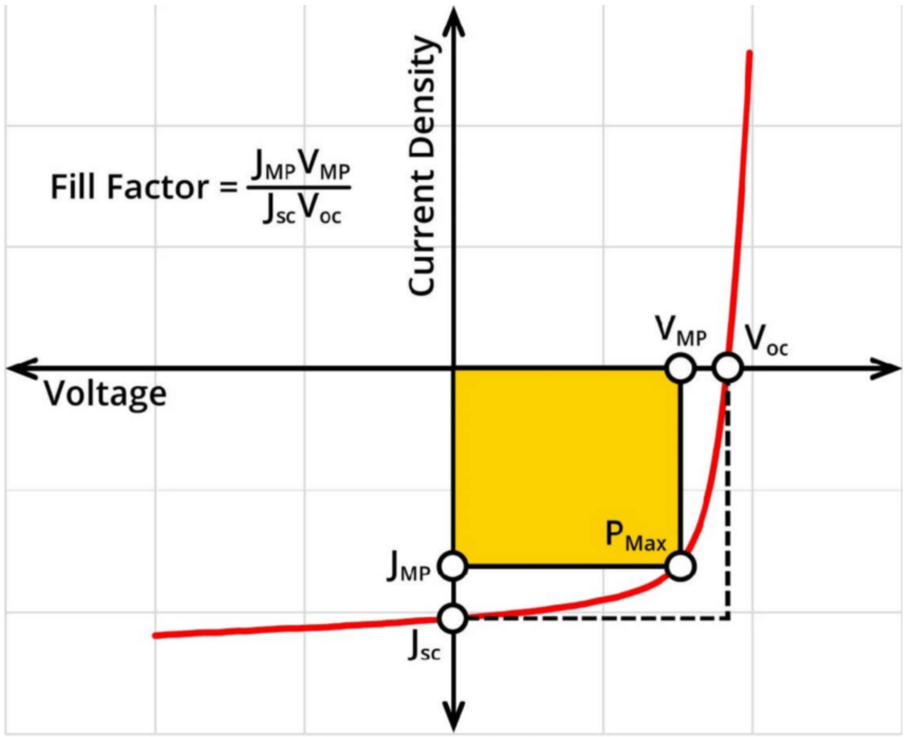

Figure 8: Typical IV curve of a solar cell plotted using current density, short-circuit current density (Jsc), open-circuit voltage (Voc), current and voltage at maximum power maximum power point (PMax), and fill factor (FF).[37]

Power conversion efficiency is another important parameter of solar cell. The power conversion efficiency is defined as the ratio of the optical power out (P_{Lout}) and the electrical power in (P_{Ein}). This includes power loss due the difference between the external applied voltage and the energy of the emitted photons, which includes voltage drops across the internal resistance. [38]

$$\eta_{\text{pow}} = \frac{P_{\text{Lout}}}{P_{\text{Ein}}}$$

Different types of solar cells

Solar cell as a photovoltaic device basically works based on the principle that when solar cell is illuminated by sunlight, it generates creating photovoltaic effect- a phenomenon which converts sunlight into electricity. A number of factors including cell material, cell length, intensity, quality of the light source determines the amount of electricity produces. Generally photovoltaic cells are classified based on active materials used in the manufacturing. Solar cell are recently being classified based on their material complexity. [39]

According the device structure solar cells are mainly two type. One is wafer-based and the other is thin-film technology. Wafer-based solar cells are mainly made of slices of semiconductors derived from ingots[40] and the think-film based solar cells are made with glass subtract or polymer material where semiconducting materials are deposited for the formation of device structure. [41]

There are basically three different type of wafer-based solar cell. I)crystalline silicon, ii) Gallium arsenide and iii) III-IV multijunction. Crystalline silicon based solar cells are most popular solar

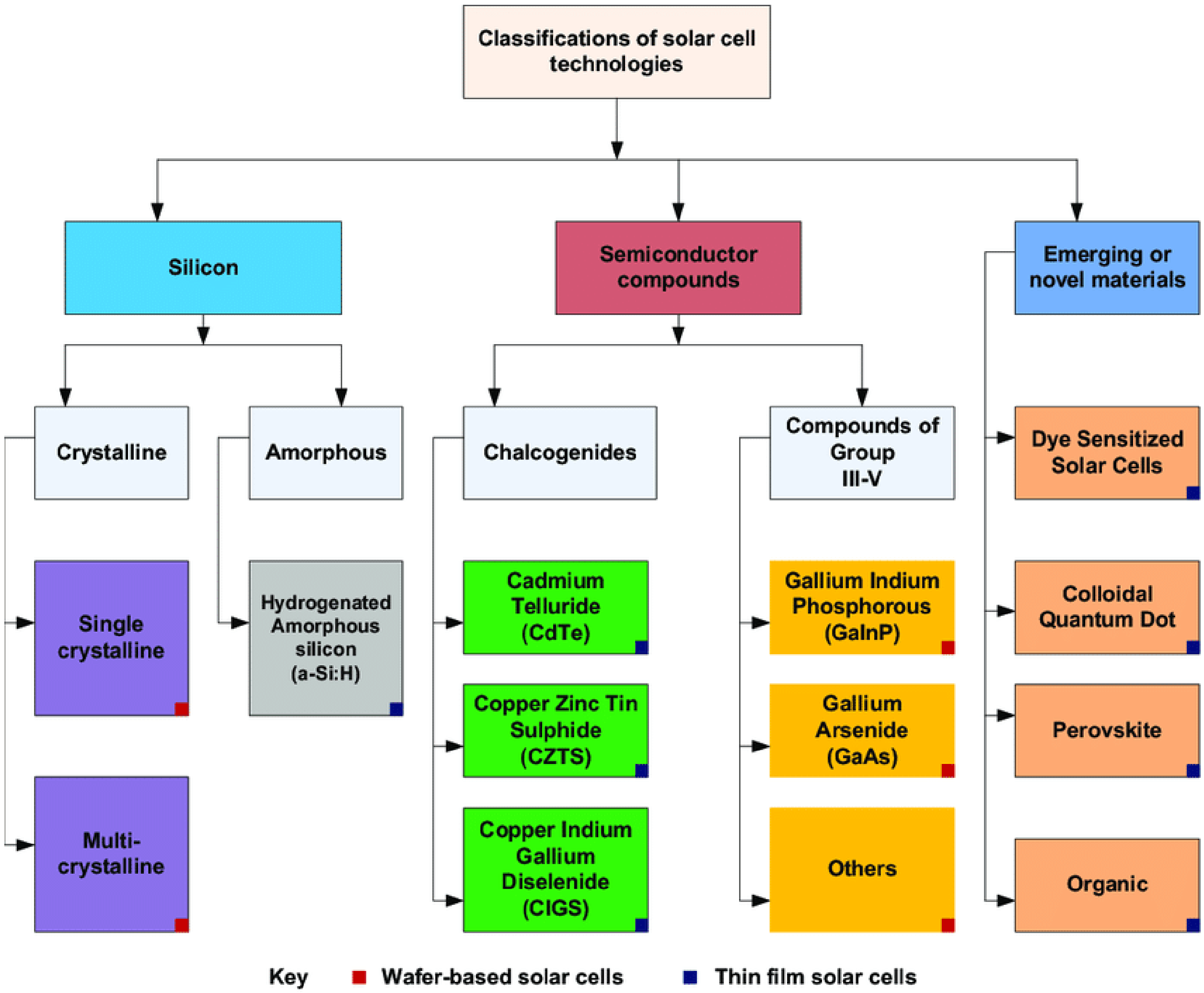

Figure 9: Types of solar cell [42]

cells sold commercially and has highest photo conversion efficiency and contains nontoxic chemicals [43]. Despite having many advantages, disadvantage is that c-Si is a poor absorber of light due to its indirect energy bandgap of roughly 1.1 eV at room temperature[44], encouraging the use of fairly thick, rigid and brittle wafers to absorb most of the incident light in the absence of advanced light-trapping mechanism. [39,44]. Even after having some disadvantages, crystalline silicon wafer based solar cells constitutes roughly 90% global module production and are one of the most developed technology.[45]

Recently, scientists are focusing more on fabricating solar cells based on different new material which can be highly efficient and nontoxic as well. From that the concept of having sustainable solar cell is being developed considering the maintenance of future generation's need as well [46]. From that thought different new type of thin film solar cell like perovskite solar cell, organic solar cell, dye sensitized solar cells, colloidal quantum dot solar cells are being invented. Improving these solar cells directly relates to the human empirical sustainability outcomes of security, opportunity, and health from affordable, abundant clean energy, which have cross-societal, multi-regional, and transgenerational dimensions and directly follows[47] the sustainability aspect like social, economic and environmental needs.[47]

Perovskite solar cell

Perovskite solar cell (PSC) is one of the latest and popular innovations in PV technologies. Perovskite solar cell's geometries are largely based on dye sensitized solar cell (DSSC) [48]. PSC is a modified adaptation of DSSC using their Ru or different sensitizer to transfer the photons into electron-hole pairs. Perovskite is mainly calcium titanium oxide mineral named after a Russian mineralogist. Miyasaka and other researchers [49–51]were apparently the first to report photovoltaic results for perovskites; they were attracted by the self-organization potential of perovskite in the nonporous TiO_2 layer of dye-sensitized cells. And it entails all the minerals which crystalizes in the same ABX_3 structure where A and B are the cations and X in the anion [52]. For hybrid organo-lead perovskites, A is a monovalent organic cation and B is generally Pb(II) or Sn(II) and X is an halogen anion such as I^-,Br^-,Cl^- [50].

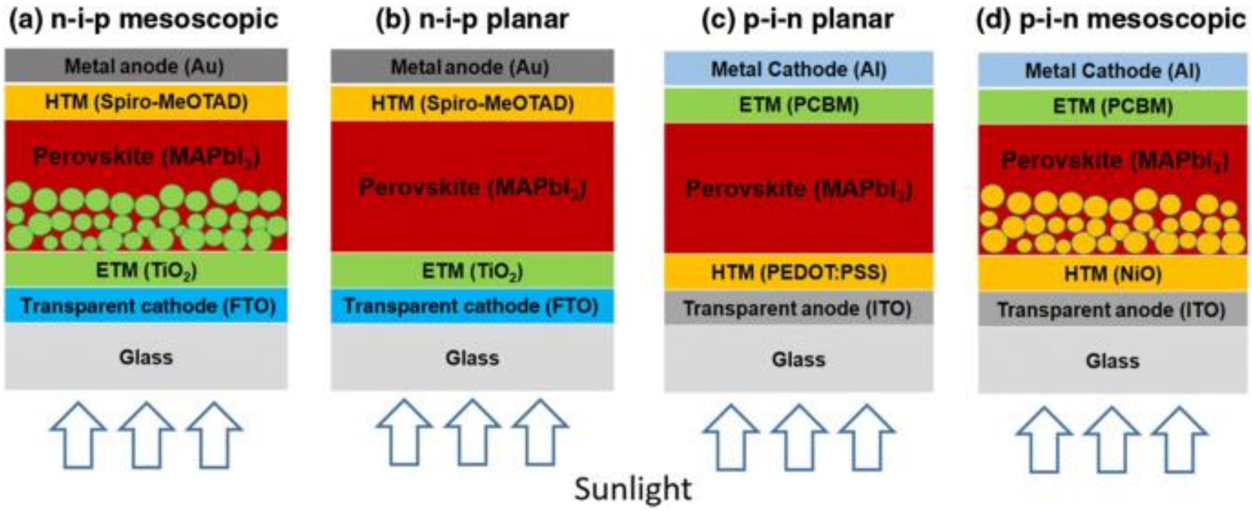

Figure 10: Architecture of perovskite solar cell [53]

Though PSC has good efficiency but still there are some drawbacks as the morphology, material stability, moisture affinity, cell instability and the use of toxic chemicals mostly like Lead. The two most common architectures are the so called mesoscopic and planar as shown in figure 10 and these are also called n-i-p according to their arrangement of semiconductor layer. At first, a compact thin layer of TiO_2 was used as hole blocking layer on top of the FTO/ITO glasses. But now a thicker and nano porous TiO_2 layer is used. In recent reports it is shown that incorporating metal NPs, e.g., Au or Ag, on TiO_2 nanowire surfaces can enhance the light-to-current conversion efficiency[54–60].

In addition, though the efficiency of PSC is higher, the material cost for PSC is higher as well which is a major drawback. The materials used in PSC like HTM SPIRO-MeOTAD is even more expensive than using platinum. This property of PSC makes it less sustainable source in the long run. Now a days different doped and undoped inorganic contacts materials have been used like NiOx[61–63], CuOx[64], CuI[65–67], CuSCN[68,69], ZnO[70,71] etc. After working for years on improvement of PSC efficiency, it is now showing a good result as well shown in figure 11.

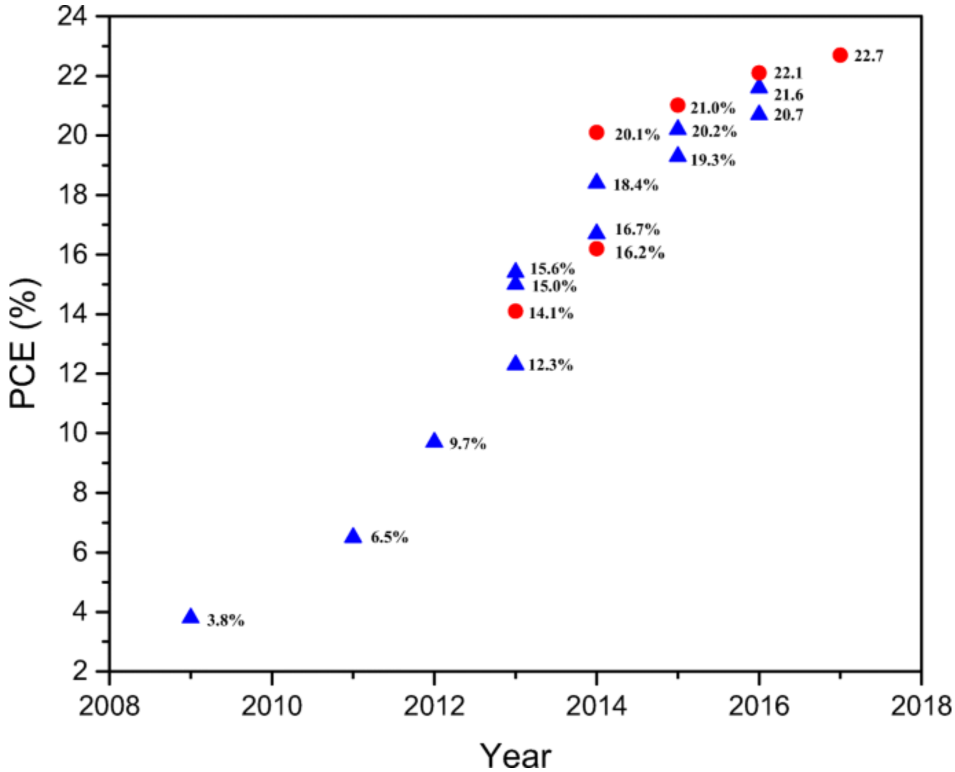

Figure 11:The progress in PCE of PSCs[53]: 3.8%[72], 6.5% [73], 9.7% [74], 10.9% [75], 12.3% [76], 15.0% [77], 15.4% [78], 16.7%[79], 18.4%[80], 19.3% [81], 20.2% [82], 20.7% [83], and 21.6%[84]. Values in red represent certified efficiencies [85]

Dye sensitized solar cell (DSSC)

Dye sensitized solar cell(DSSC) is one of most promising photovoltaic device for converting solar energy to electricity as it is unique, low cost, low maintenance, easy to fabrication and relatively high photo conversion efficiency [24,86–92]. In a dye sensitized solar cell, photon from sunlight is captured by photosensitizer which absorbed on a thin layer of semiconductor material.

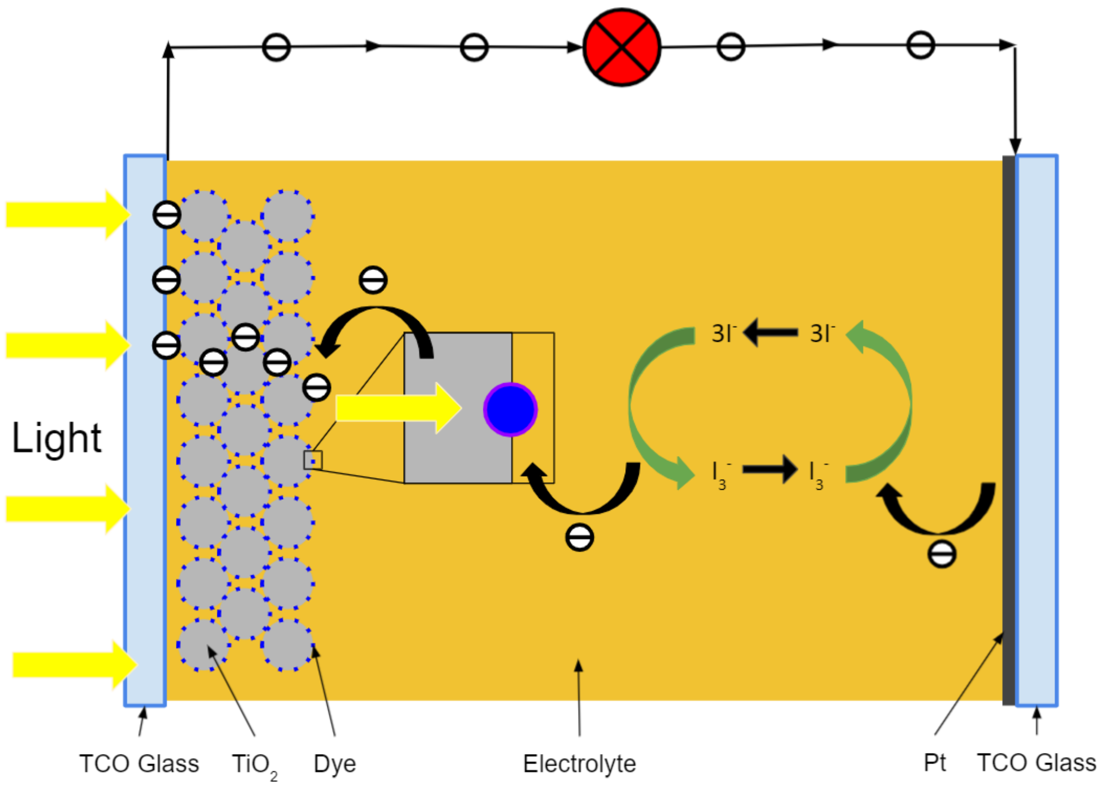

Figure 12: working principle of DSSC

In a dye sensitized solar cell there are generally few parts like[93]

1. coated with Transparent Conductive Oxides
2. the semiconductor film, usually TiO_2
3. a sensitizer adsorbed onto the surface of the semiconductor
4. an electrolyte containing a redox mediator
5. a counter electrode capable of regenerating the redox mediator like platinum

Whereas other PV technologies used semiconductor materials in the solid-state condition to transfer electron to produce electricity, DSSC uses liquid electrolyte to transfer the electron to counter electrode. DSSC has photo conversion efficiency of 12.3%[94]. The main advantages of DSSC are lower manufacturing cost, little use of low-cost material and easily available materials, easy to assemble and flexible modules, the flexibility to incorporate any material in the device. Despite having numerous advantages, there are still some drawbacks like long term stability in high temperature or in absence of sunlight, low absorption coefficient, flexibility.

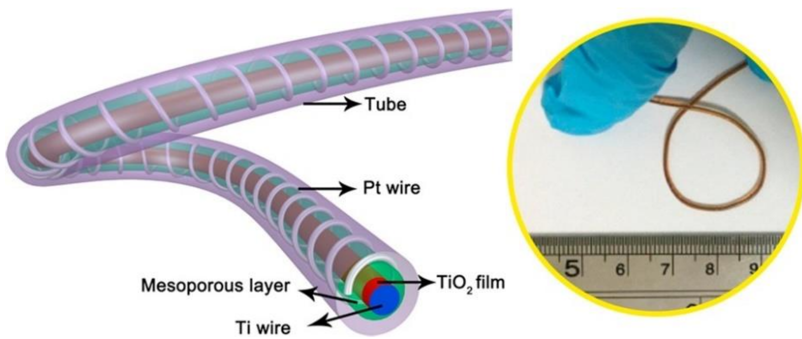

Figure 13: A diagram of a flexible solar cell fabricated with Ti wire[95]

Considering these issues, in this project the focus was fabricating a flexible electrode. Our commercial market is growing rapidly inventing more flexible and user-friendly device everyday with more efficiency. But the challenge is making a photovoltaic device with good efficiency, flexible, user friendly but environment friendly [96–99]. So as a flexible, wearable, potential renewable fiber shaped dye sensitized solar cell has been very popular now a days. There are few substrates that are used as flexible electrode. Specially Titanium wire and carbon nanotube yarn have been used as flexible electrode.

Colloidal quantum dot solar cell(QDSC)

Quantum dots (QDs) are semiconductor particles a few nanometers in size, having capacity of transferring electrons creating optical and electronic properties that differ from larger particles due to quantum mechanics. That's why they are also used as a semiconductor material for solar cell which is called quantum dot solar cell. [100].

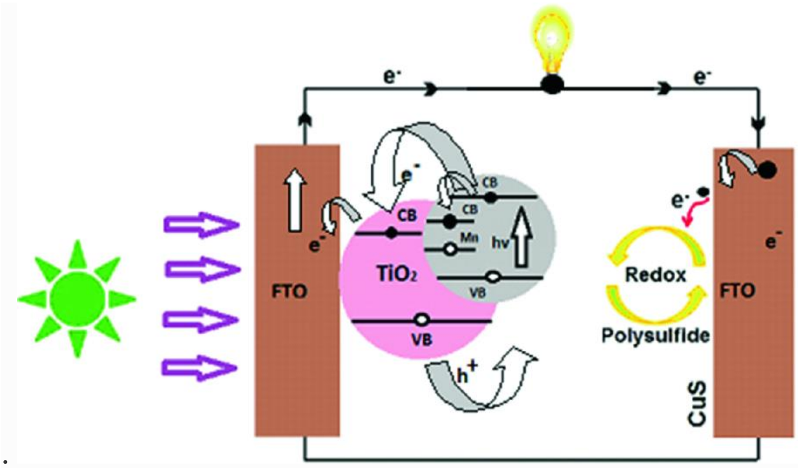

Figure 14: A schematic diagram of quantum dot solar cell[101]

Quantum dot materials are suitable for photovoltaic materials because their band gap, optical and electrical properties can be easily altered by changing the size of the nanoparticle. The flexibility with controlling the bandgap has benefited QDSC to absorb any solar spectrum making room for efficient harvesting of near-infrared photon [39]. Processing of quantum dot basically involves solution making process so it is really easy to incorporate in any solar cell fabrication process [100]. Quantum dot solar cell mostly follows basis of dye sensitized solar cell and the difference is QDSC does not include extra dye or sensitizer [102]. There are still some limitations of low photo conversion efficiency and still there are less work on flexible photovoltaic device. That is why this project mainly focuses on fabricating flexible/fiber shaped quantum dot solar cell

CHAPTER III

EXPERIMENTAL SECTION

Preparation of working electrode

For working electrode Ti wires were used (φ = 250 μm). The wires were cut into length of 5-6cm and cleaned by ultrasonicating by acetone, ethanol, and deionized water respectively for 15 minutes. Then the wires are treated with 35ml of 2.5M NaOH solution in an autoclave for 12 hours at 220 degree Celsius. After that, the wires removed from the autoclave and cooled to room temperature. Afterward, the wires were again cleaned with deionized water and ethanol for several times and dried at 60 degree Celsius for 10 minutes. Then the wires are immersed in 1M HCL for 2 hours. After 2 hours the wires are again treated with 0.02M H_2SO_4 for 4 hours in 100 degree Celsius in a Teflon-lined stainless-steel autoclave. Next, the wires are washed with deionized water and acetone to remove extra acid solution. Then the wires are annealed for 30 minutes in 500 degree Celsius to get Ti wire with TiO_2 nanowires (NWs), which were used as the photoanode.

Preparation of Lead Sulfide (PbS) Quantum Dot on working electrode

For the deposition of PbS quantum dot sequential ionic layer adsorption and reaction (SILAR) were used. In this experiment four different type of cell was fabricated with 10,15,20,25 SILAR and their output was compared. In this process, 0.06M solution of $Pb(NO_3)_2$ was made with 1:1 methanol and DI water. Also, 0.3M of Thiourea solution was made with 30 ml of Mili-Q water. The wires were first dipped in $Pb(NO_3)_2$ solution for 60s and then to remove extra chemical it was dipped into ethanol for 30s followed by dipping into Thiourea solution for 60s. When the desired SILAR was obtained, the working electrode is dried in 100 degree Celsius for 30 minutes.

Preparation of counter electrode

In this experiment carbon nanotube fiber (CF) was used as counter electrode. Before using CF, it was cleaned and treated several times. The carbon nanotube fibers are first dipped into acetone for 3 hours to remove wanted substances from surface. Then CFs were cleaned with acetone, ethanol, and Mili-Q water with low sonication. Then the CFs were heated into tube furnace in 350 degree Celsius for 2 hours with a light flow of air. Then the CFs were again cleaned with Mili-Q water, acetone and 2-propanol with light sonication. Then the CFs were immersed into 70% HNO3 solution for 5 hours. After that, the CFs were again cleaned with ethanol, acetone and Mili-Q water with light sonication and dried in air. Then the fibers were cut into 5-6 cm length and ready for next step. Then the CFs were dipped into0.5 M of Cu $(NO_3)_2$ for 3 minutes. Then they were dipped in 1:1 methanol and water 1M solution of $Na_2S{\cdot}9H_2O$ for 3 minutes. Then the CFs were rinsed with Mili-Q water to remove extra substances and calcined in 450 °C for 30 minutes. Before using, the CFs were sputtered with Pt with 40 mA for 45s. Now the carbon nanotube fibers are ready to use as counter electrode.

Fabrication of cell

Working electrode Ti wires with 10,15,20,25 SILAR is wrapped with carbon nanotube fiber with Cu_2S on its surface to make 4 different type cells. Then the cells were inserted into a capitally tube and electrolyte was injected into the capillary. This electrolyte is a polysulfide base electrolyte made with 1 M Na_2S, 2 M S, and 0.2 M KCl in 1:1 methanol and water solution.

CHAPTER IV

RESULT AND DISCUSSION

The morphology of Ti wire with different SILAR layers of quantum dot were characterized by scanning electron microscopy (SEM). Before doing SEM analysis the electrodes were sputtered with Au target for 45s. In figure 15(d) is the SEM image of Ti wire along with TiO_2 nanowire and PbS quantum dot layer. The structure gives an indication of nanostructured anatase TiO_2 nanowire [103] and the tip with 10 SILAR Pbs quantum dot. As the thickness of quantum dot increases, it can be shown from the other pictured that cluster of quantum dot. In The figure15 (a), it is PbS quantum dot with 15 SILAR process. Here the nanowire can be seen but still less than 10 SILAR as the thickness of quantum dot has increased. In the figure 15(b) which has 20 SILAR PbS quantum dot has a more homogenous layer. [104] There are big cluster of quantum dot on the nanowire noticed in the SEM image. For the figure 15(c), it is for 25 SILAR process and it is slightly different than 20 SILAR process. The cluster of quantum dot are less uniform than 20 SILAR and disoriented. To be sure about the cluster of particles, EDS analysis was done on all four types of electrodes. EDS analysis is used for the elemental analysis or chemical characterization of a sample. After doing EDS analysis on four different type of electrode, it was noticed that they all show similar kind of chemical which are Ti, Pb, S, O, Au which are the desired chemicals. EDS analysis of that particle cluster shows the evidence of synthesis of PbS quantum dot on TiO_2 nanowire. In the figure the upper most picture is an electrode with 10 SILAR, then 15 SILAR, 20 SILAR, 25 SILAR (bottom most).

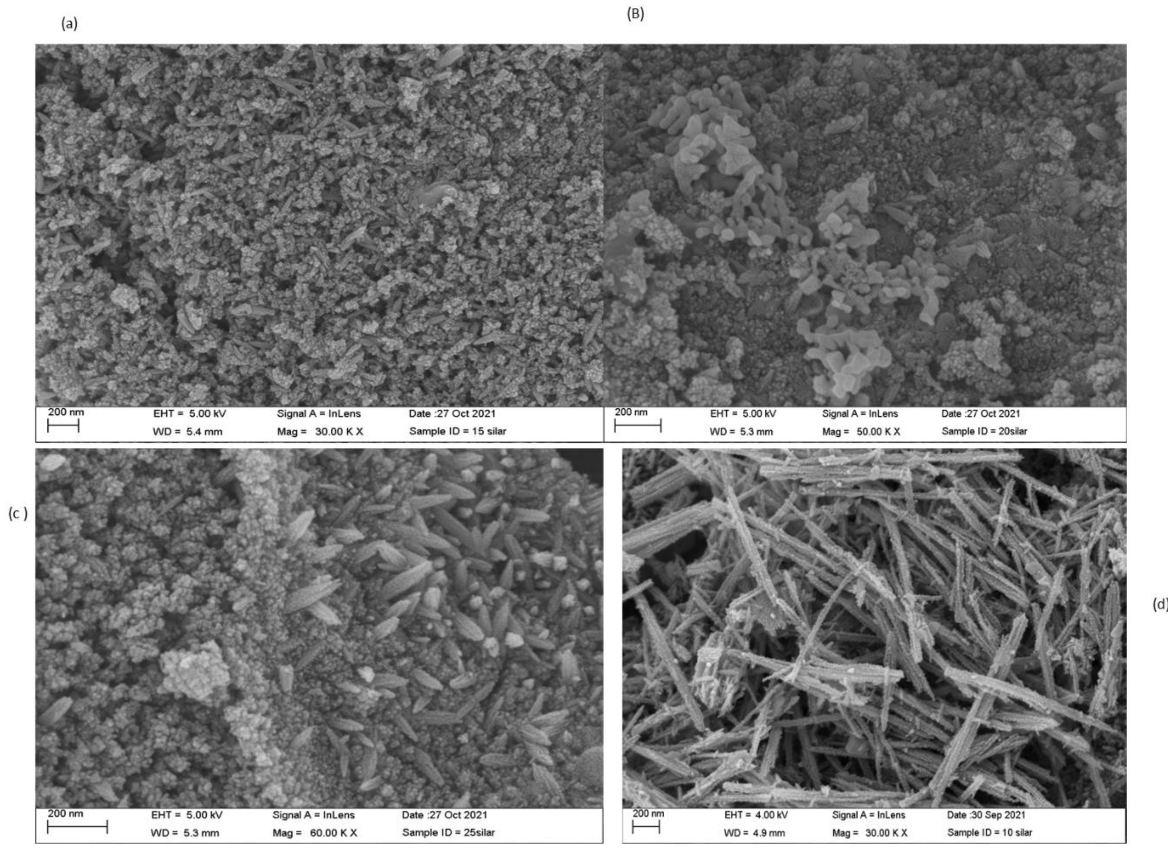

Figure 15: SEM images of (a) 15 SILAR layer cell (b)20 SILAR (c) 25 SILAR (d) 10 SILAR

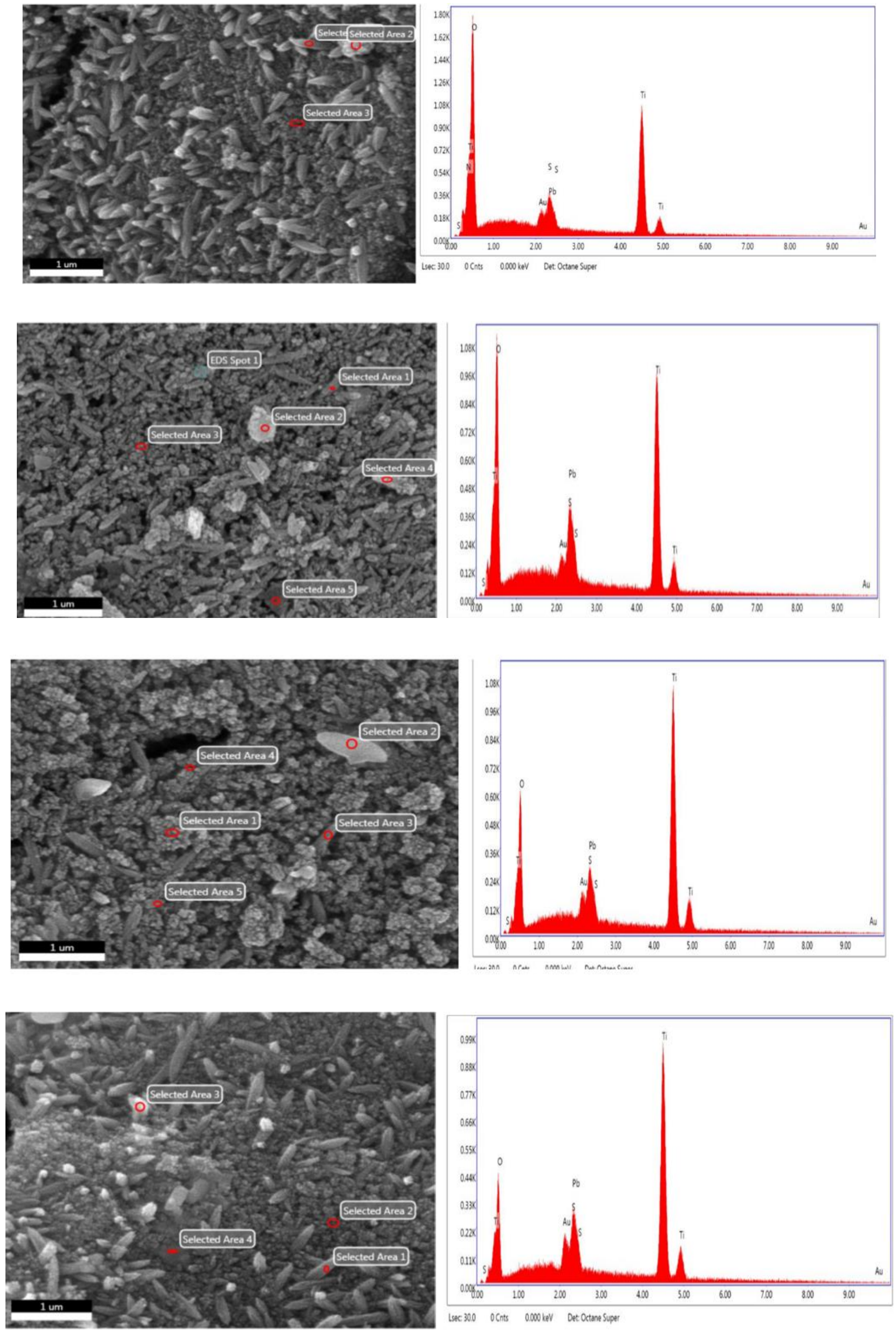

Figure 16: EDS analysis for 10 Silar,15 SILAR, 20 SILAR and 25 SILAR process

The XRD analysis shown in Figure 17 were used to analyze structure and orientation of the PbS quantum dots sensitized with anatase nanowire TiO_2 photoanodes 1, 2, 3 and 4 prepared with 10, 15, 20,25 SILAR cycles respectively. To XRD analysis with Ti wire, the wires must be prepared in a special manner. The sample holder for XRD is round shape. To fit the wire, a glass slide was cut into small pieces and then attached to the glass slides with both sided carbon tape.

In the figure, Anatase titanium oxide shows the diffraction peaks at 2θ of 37.4 °,39.2 °, 43 °, 53.9°, 63.1°,73.2°, 77° respectfully which are indexed as crystal planes (101), (004), (200), (105), (211), (204), (116), (220), and (215)[105]. These peaks are mainly indication of proper synthesis of anatase TiO_2. Here the peak at 53.9°, 63.1°,73.2° also aligns with the peak coming from PbS quantum dot [106]. The peaks obtained here in the XRD analysis reveals all expected phases to be present in crystalline form [107].

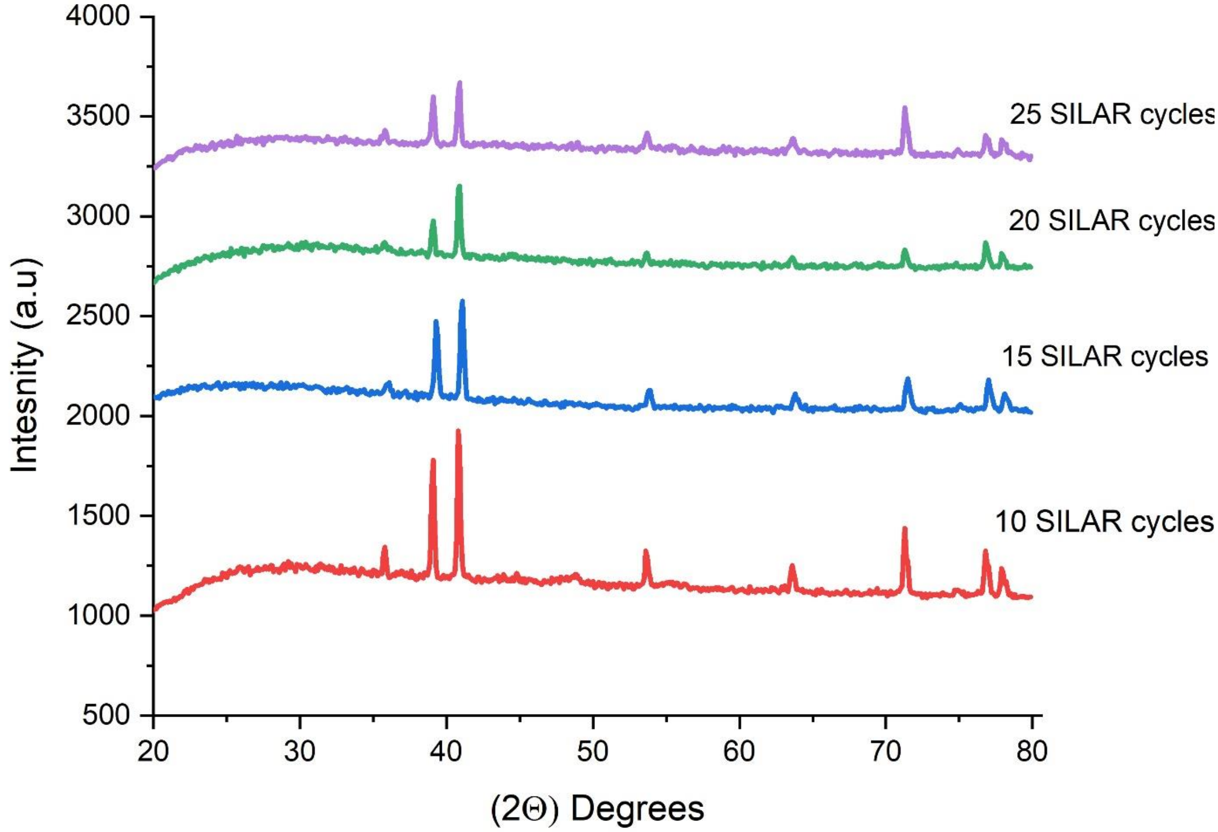

Figure17: XRD analysis of nanowire TiO_2 electrode with PbS quantum dot with 10 SILAR, 15 SILAR, 20 SILAR, 25 SILAR

Photovoltaic characterization

The devices were fabricated according to figure 18. There are four different cells with quantum dot 10,15,20 and 25 SILAR. It was observed that when the quantum dot was applied with more SILAR, the efficiency and FF was increasing until a certain point when the outcome started decreasing.

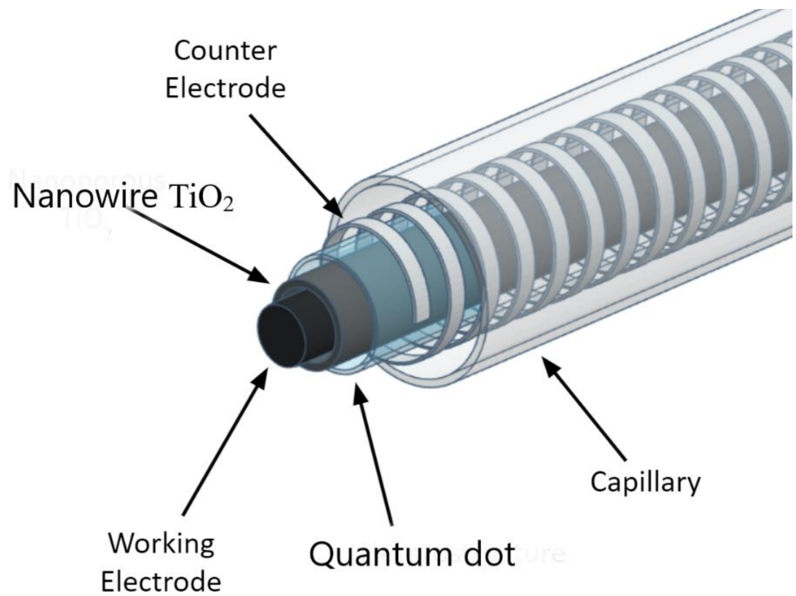

Figure 18: Schematic diagram of the device

In this experiment, Ti wire was used as working electrode with nanostructured TiO_2 layer and then PbS quantum dot with different thickness. The photovoltaic cell characterization was carried out under AM 1.5 illumination using versastat with solar simulator. The photovoltaic property was carried out for four different type of cell having 10 SILAR, 15 SILAR, 20 SILAR, 25 SILAR and a current density vs potential graph has been drawn in Figure 19. While taking the measurement it was noticed that with less thickness of quantum dot for 10 SILAR cell, the current density is quite low, and it ranges closed to 1.269758941 mA/cm^2. When the thickness of quantum dot was raised to 15 SILAR, both the current density and open circuit voltage increased.

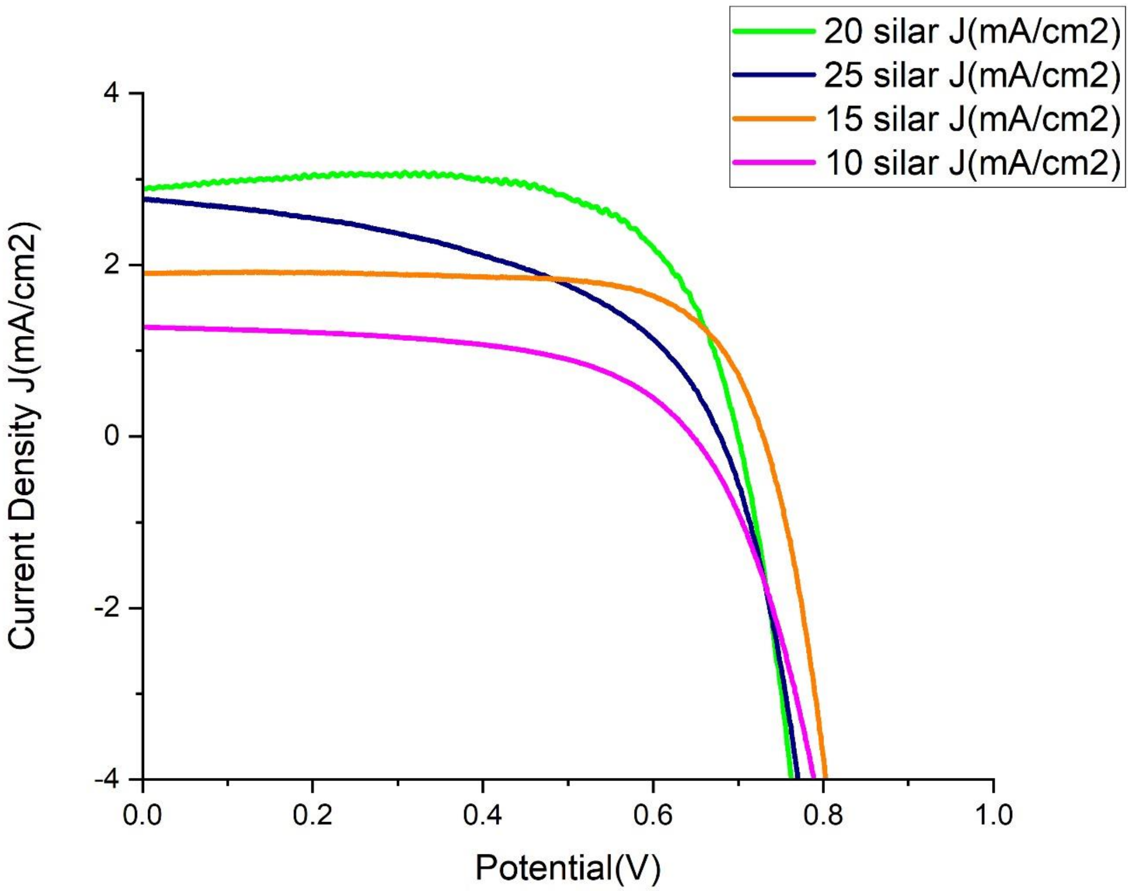

Figure 19: J-V curve of four different cells

With the cell of 20 SILAR quantum dot, current density and open circuit voltage has increased more. But after the thickness of layer increases more, the photovoltaic performance of 25 SILAR. It is assumed when the size of quantum dot increases, the stability and performance of quantum dot decreases. [108]

In the figure 20(a), it shows the variation of current density and efficiency with respect to different cell. From the graph the current density increases but the efficiency drops after 20 SILAR

cell. So, the efficiency increases from 10 SILAR-20 SILAR but then drops at 25 SILAR cell. In the figure 20(b), it shows the variation of fill factor and efficiency with respect to different cell. In this figure we can see that the fill factor and efficiency both decreases when the thickness of quantum dot increases after a certain point. Also, in the figure 20(c), we will see that the efficiency changes with respect to thickness of quantum dot in different cells. From the figure 20(d), the variation of current density and fill factor with respect to different cell is shown. We can see the current density increases but the fill factor does not increase with the increasing thickness of quantum dot.

There are many reasons which can affect the performance of a solar cell. If there is any contamination while preparing the working or counter electrode it would affect the performance. If the cells absorb moisture, that will affect the performance. Maintaining temperature while fabricating and synthesizing all the materials is very important for a solar cell. In this project, Sulfur based electrolyte is used and o leakage was spotted while working on the project.

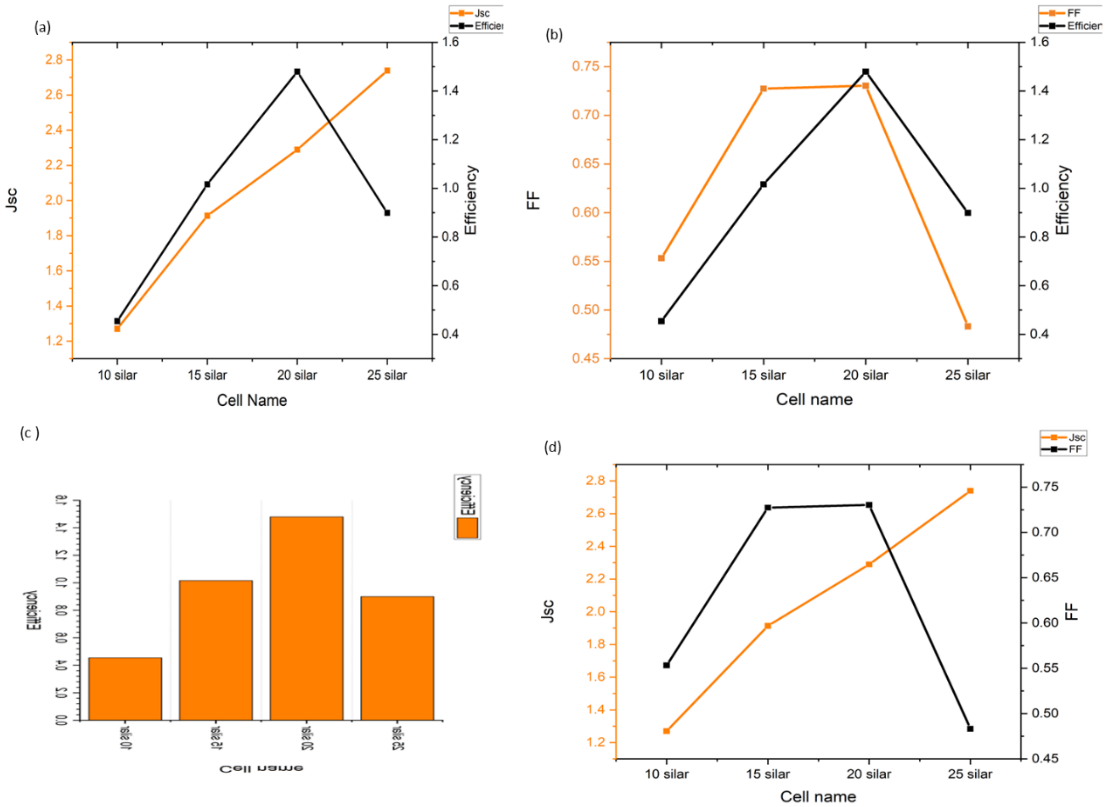

Figure 20: (a) variation of Jsc and efficient (b)variation of fill factor and efficiency (c) bar diagram of efficiency compared to the cell (d) variation of j_{sc} and fill factor

Table 1 is the summary of the total photovoltaic performance of PbS quantum dot solar cell. In this table, all the result has been summarized and compared according to different thickness of quantum dot. When we compare the photovoltaic properties of the PbS quantum dot solar cell, we will see that the efficiency for 10 SILAR cell is lower than other different cells. When the thickness increases, the efficiency and current density also increases. After certain thickness, the efficiency starts decreasing again because of the steric hinderance of the quantum dot.

WE	Jsc (mA/cm^2)	Voc (V)	power conv efficiency (%)	FF
10 SILAR	1.269758941	0.64684	0.454454319	0.553314546
15 SILAR	1.913134478	0.73027	1.016292841	0.727427822
20 SILAR	2.895351921	0.6996	1.479529292	0.730419584
25 SILAR	2.73907028	0.67966	0.899604944	0.483233403

Table 1: Photovoltaic Properties of QDSC Using Different WEs

CHAPTER V

CONCLUSION

Solar cell has a great potentiality to integrate into next-generation power supply keeping a balance within the increasing amount of power consumption every year. The demand of power will be increasing every year, but the energy sources will still remain constant. Keeping that in mind, this project not only just focused on an alternative energy source, it also focused to produce a flexible and more user friendly solar cell. With that ambition, PbS quantum dot was synthesized in this experiment and instead of v using flat cell like FTO/ITO glass, Ti wire was used as working electrode and carbon nanotube yearn with CuS layer was used. Four different type of cell was prepared in this experiment and their efficiency is evaluated. Each of them is fabricated with different SILAR quantum dot. The crystalline structure of working electrode will be evaluated by X-Ray diffraction and the morphology will be analyzed with SEM. From the I-V curve, it was seen that with the increasing SILAR, efficiency was increasing too but at one point the efficiency started decreasing. Highest efficiency was found 1.47% from 20 SILAR cell with current density 2.895351921 mA/cm^2 and open circuit voltage 0.6996 V.

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BIOGRAPHICAL SKETCH

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