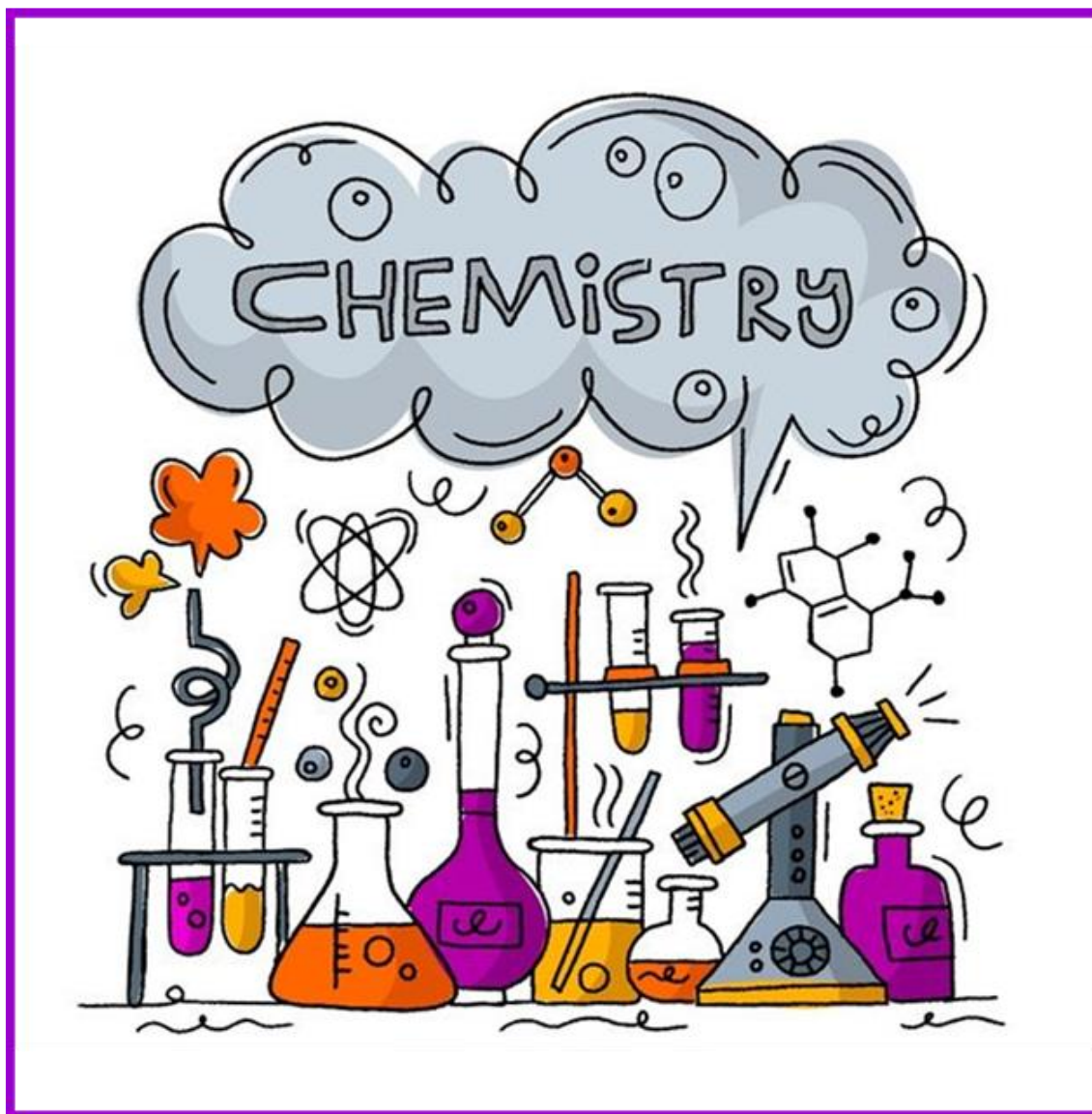


Chapter 2

Experimental Section



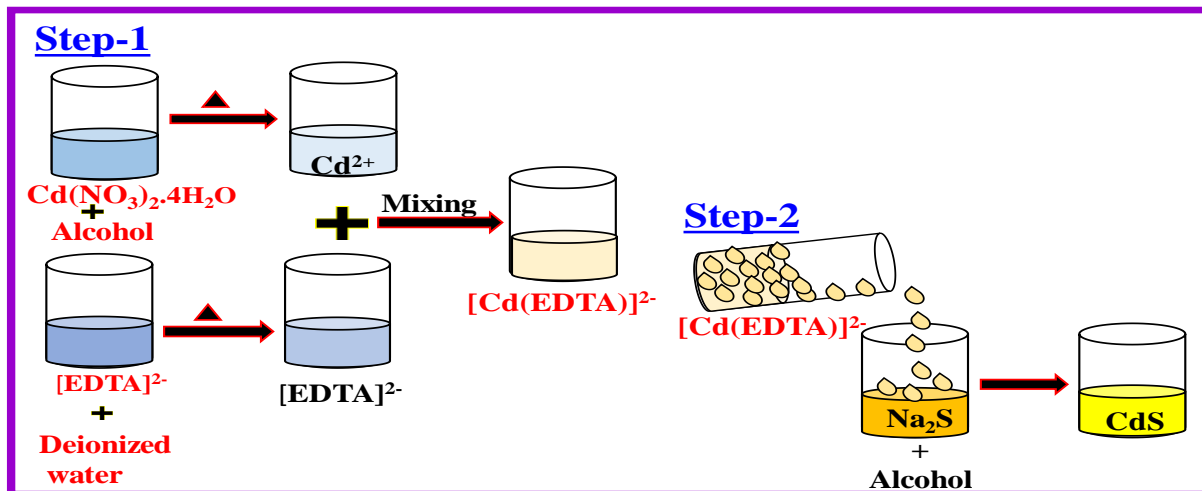
2.1 Synthesis of Quantum Dots

2.1.1 Materials

Cadmium nitrate (Sigma-Aldrich), cadmium oxide (CaO, Sigma-Aldrich), sodium sulphide (Himedia), Octadecene (ODE, Sigma-Aldrich), selenium (Se, Sigma-Aldrich), trioctyl phosphine (Sigma-Aldrich), 3-mercaptopropanoic acid (Sigma-Aldrich), sulfur powder (Sigma-Aldrich), oleic acid (Sigma-Aldrich), Trioctyl phosphine oxide (Sigma-Aldrich) TiO₂ paste (Solaronix), graphite flack (Sigma-Aldrich), sodium hydride (NaH), multiwalled carbon nanotube (Sigma-Aldrich), poly(tetramethylene glycol) (PTMG, Mn = 2900 g mol⁻¹), butanediol (Sigma-Aldrich), 4',4'-diphenylmethane diisocyanate (MDI, Sigma-Aldrich), 1,4-trans cyclohexylenene diisocyanate (Sigma-Aldrich), N,N-dimethylformamide (DMF Himedia), titanium tetrachloride (TiCl₄, Stern), N,N-dimethylacetamide (DMA), Dibutyl tin dilaurate (DBTDL), propane sultone (Sigma-Aldrich), Sulphuric acid (Sigma-Aldrich), ethanol and Nitric acid (Sigma-Aldrich), were used for the synthesis process.

2.1.2 Synthesis of the CdS Quantum Dots via Solution Mixing Method

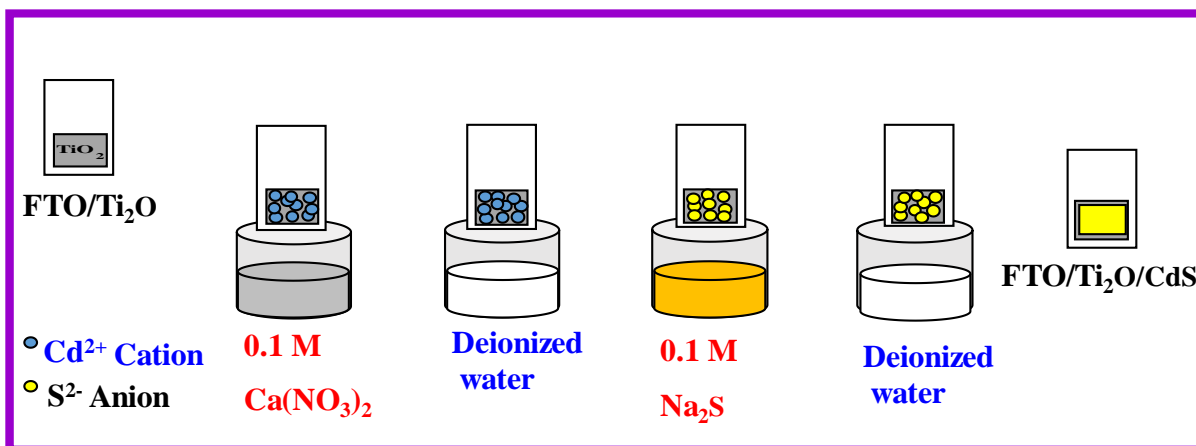
The CdS quantum dots was synthesized through previously reported method.[107] Initially, 0.4 M cadmium nitrate was dissolved in 10 mL of ethanol and 0.114 M ethylenediamine tetra acetic acid (EDTA) was dissolved in 20 mL deionized water with rapid stirring, and cadmium solution were mixed in EDTA solution under constant stirring and further heated at 100 °C for 2 h and maintaining the p^H of the solution approximately ~ 5. Further, added the sodium sulphide solution (0.11M) dropwise in to the reaction mixture and a light-yellow precipitate was obtained after 30 min and the synthesized quantum dots were washed with water and ethanol various time and centrifuged at 5000 rpm for the 5 min to remove the unwanted species. The prepared CdS QDs were dispersed in chloroform and kept at lower temperature (-5 °C).



Scheme 2.1: Schematic synthesis of the CdS quantum dots via solution mixing method.

2.1.3 Synthesis of the CdS Quantum Dots via SILAR Method

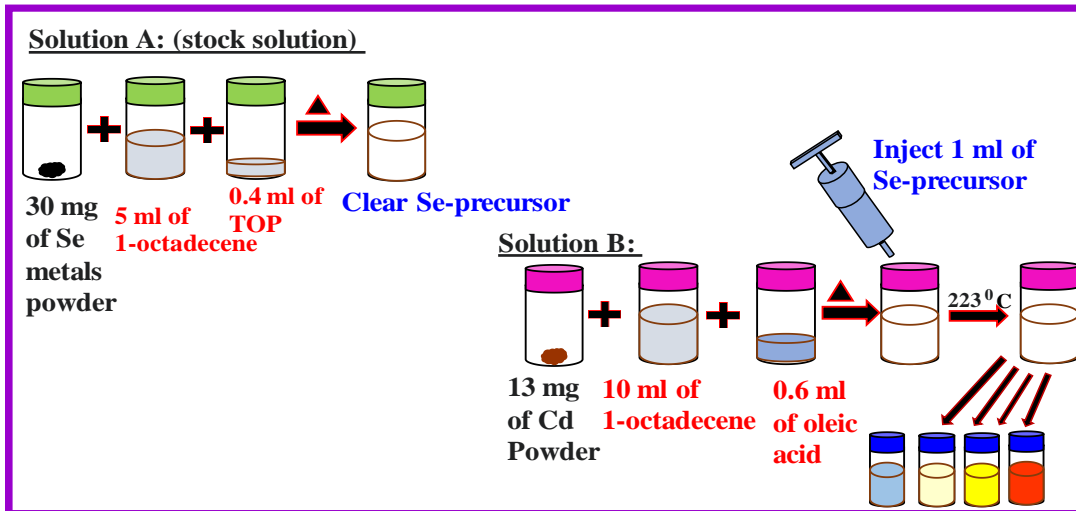
The CdS quantum dots also synthesized by using the SILAR method.[108] This method was involved the two steps process, first step involves the preparation of the aqueous solution of the cadmium nitrate and sodium sulfide and after that, the photoanode was dipped in the cadmium nitrate solution and washed by using the deionized water and dried at 50 °C, further dipped the photoanode in sodium sulfide solution and washed by using the deionized water and dried this is known as one SILAR cycle and this cycle was repeated for the deposition of optimum amount of the thickness of CdS QDs.



Scheme 2.2: Schematic diagram of the growth of the CdS quantum dots via SILAR method.

2.1.4 Synthesis of the CdSe Quantum Dots via Hot Injection Method

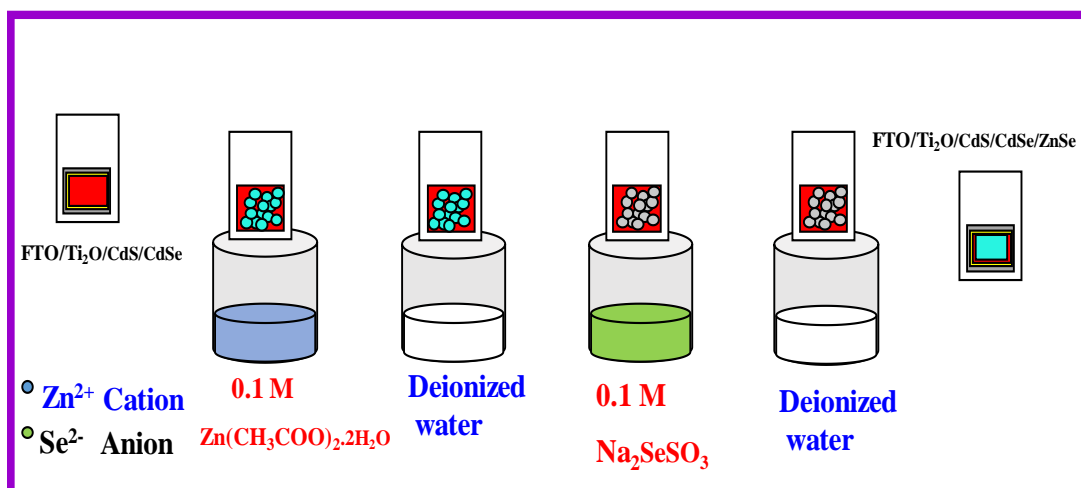
The CdSe QDs are synthesized by using the hot injection method with some changes.[109] This method was involving the two steps. Initial step involves, preparation of the selenium precursor by dissolving the selenium powder (30 mg) in 5 mL of octadecene and 0.4 mL of the trioctylphosphine with rapid stirring to obtain a transparent solution. Second steps involve the cadmium oxide (13 mg) dissolved in a mixture of octadecene (10 mL) and oleic acid (0.6 mL) in the presence of nitrogen environment and further heated at 223 °C until the solution becomes clear and that temperature, 1 mL of the selenium precursor was injected in reaction mixture and immediately 1 mL of the aliquot was withdrawn with help of Pasture pipette at various time interval to obtain various sizes of CdSe QDs. The synthesized CdSe QDs was washed by ethanol and centrifuged at 3000 rpm for 5 min and repeated this process at least five times to obtained the pure CdSe QDs. The prepared CdSe QDs was dispersed in solvent (hexane) and stored at room temperature.



Scheme 2.3: Schematic diagram of the synthesis of CdSe quantum dots.

2.2 Deposition of the ZnSe Passivation Layer

SILAR technique was used to deposit the ZnSe passivation layer on TiO₂/CdS/CdSe photoanode.[110] The prepared TiO₂/CdS/CdSe photoanode was alternatively dipped in an aqueous solution of zinc acetate dehydrated (0.1M) for 5 min at 50 °C and was washed with deionized water and dried and further dipped in Na₂SeO₃ at 50 °C for 5 min and the cycle was repeated three times, resulting in the optimum amount of ZnSe passivation layer was deposited on the TiO₂/CdS/CdSe photoanode.



Scheme 2.4: Schematic diagram for the deposition of ZnSe passivation layer.

2.3. Synthesis of the Graphene Oxide

The graphene oxide was synthesized by using the previously reported Hammer's method with few alterations.[111,112] In this method, graphite flack (3.0 g) was dissolved in the mixture of the concentrated H₂SO₄ and H₃PO₄ (9:1 volume ratio) and added KMnO₄ (18 g) in the reaction mixture, further it was heated at 50 °C with rapid stirring for 12 h, after that the reaction mixture was cooled at 25 °C, followed by the addition of the 3 mL of H₂O₂ (30%) and washed with dilute HCl, ethanol, and distilled water respectively, and centrifuged until its p^H becomes neutral. Further it was dried at 70 °C for 48 h.

2.4 Functionalization of MWCNTs

The functionalized multiwalled carbon nanotubes (f-MWCNT) were synthesized by using the previous reported method.[113,114] In this method, 100 mg of pristine MWCNT was dissolved in the 200 mL mixture of the sulphuric acid (95%) and nitric acid (95%) with 3:1 in a 500 mL in a round bottom flask and heated to 100 °C for 4 h, further cooled at 50 °C and ultrasonicate the mixture for 24 h. The dispersed mixture was diluted with water and washed with deionized water until the pH of the dispersed mixture was reached to neutral, and the samples was dried in vacuum oven under inert atmosphere at 40 °C for 72 h resulting the functionalized carbon nanotube (f-MWCNT) was obtained.

2.5 Synthesis of Polymer

2.5.1 Synthesis of the Thermoplastic Polyurethane Polymer

The polyurethane polymer was synthesized by using the previous reported method with some alteration,[112,115] the synthesis of the polyurethane polymer involves the Two steps process, In the first step involve the preparation of the prepolymer by mixing of the 4'.4'-diphenylmethane diisocyanate (MDI) and poly(tetramethylene glycol) monomers in N,N-dimethylformamide (DMF) solvents at 70 °C in the presence of the nitrogen environment with rapid stirring for 3 h, further butanediol used as a chain extender and DBTLD as a catalyst was added in the reaction mixture for complete the polymerization reaction and further it was heated at the 70 °C for the 24 h and after the 24 h the reaction mixture are poured in the deionized water to obtained the precipitate of the polyurethane polymer and dried in the vacuum oven at 50 °C.

2.5.2 Synthesis of the Chemically GO-tagged Polyurethane Polymer

GO-tagged polyurethane polymer was synthesized through three stages polymerization process with some alteration.[112] Initial stage involves the prepolymer (PP) formation via mixing the monomers such as PTMG and MDI in DMF solvent at 70 °C for 3 h under nitrogen environment resulting prepolymer was formed, and 5 mg of GO added with prepolymer solution and it was heated at 70 °C for 2 h with rapid stirring to form the graphene oxide-tagged prepolymer. Further, the polymer chains were extended by adding the butanediol (chain extender) with few drops of DBTDL catalyst in reaction mixture for complete polymerization and it was kept at 70 °C for 24 h with constant stirring. Precipitate of GO-tagged polyurethane is obtained by pouring the reaction mixture in DI water and dried in vacuum at 50 °C for 72 h.

2.5.3 Synthesis of the Chemically f-MWCNTs-tagged Polyurethane Polymer

The CNT-tagged polyurethane polymer was synthesized by previous reported method with some modification.[112,116] In a typical synthesis of CNT-tagged polyurethane polymer (PU-CNT) proceed through the two steps and three stages polymerization. The first stage involve the prepolymer formation by mixing of 1,4-cyclohexylenediisocyanate and PTMG in DMF solvent at 70 °C for 3 h in the presence of the nitrogen environment to form an prepolymer, after that, 5 mg of f-MWCNT was added in the prepolymer solution and heated at 70 °C for 2 h with rapid stirring resulting CNT- tagged prepolymer (PP-CNT) was formed and further butanediol was added in polymeric solution for extension of the polymer chain and few drops of the DBTDL catalyst was added in reaction mixture for complete polymerization and reaction temperature were maintained at 70 °C for the 24 h with rapid stirring. After 24 h the reaction mixture was cooled at 25 °C and pouring in deionized water resulting precipitate of the PU-CNT polymer was obtained. The PU-

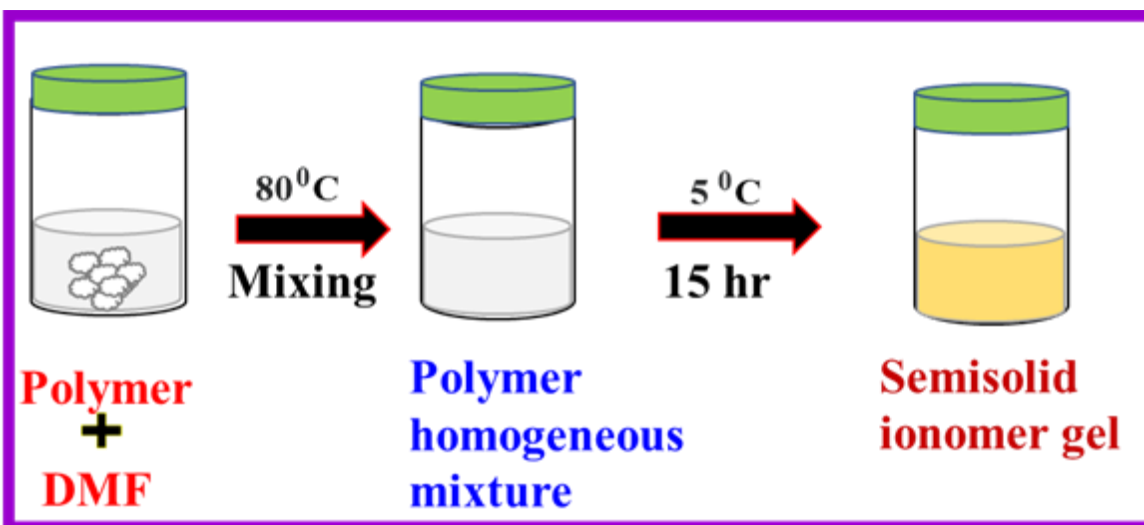
CNT polymer was dried in vacuum oven at 50 °C for 72 h, resulting obtained the CNT-tagged polyurethane polymer (PU-CNT).

2.6 Functionalization of the Polyurethane Polymer

The functionalization of the polymer proceeds via nucleophilic substitution reaction.[115,116] Initially, the polymer was dissolved in DMF solvent and heated at 50 °C with rapid stirring to obtained the homogeneous mixture of the polymer and further it was cooled at room temperature and sodium hydride was added in reaction mixture under the nitrogen atmosphere for 3 h, after that, the reaction mixture was heated at 50 °C and added the γ -propane sultone in the reaction mixture and reaction mixture was kept at 50 °C for 24 h. Further the reaction mixture was poured in the toluene to obtained the polyurethane ionomer and the ionomer washed by ethanol and dried in vacuum oven at room temperature.

2.7 Preparation of Ionomer Gel

The polyurethane ionomer was dissolved in DMF solvent and heated at 80 °C with rapid stirring to obtain the homogeneous mixture of ionomer, further the mixture was cooled at 5 °C for 18 h, resulting the semisolid ionomer gel was observed.



Scheme 2.5: Schematic preparation for the ionomer gel.

2.8 Fabrication of the QDSSCs.

2.8.1 Preparation Photoanode

FTO coated glass sheet was clean properly with the help of bath sonication through soap water, acetone and distilled water for 15 min each solvent, followed by deposition of thin of TiO₂ paste (Solar-nix) by using the doctor blade technique on FTO glass sheet. It was heated at 75 °C for 20 min to remove the organic solvent which have low boiling point and further annealed at 450 °C for 30 min, and cooled at room temperature to obtained the crystalline TiO₂ thin film on FTO glass sheet. The CdS QDs fine dispersed solution in isopropanol was prepared by ultrasonication method and the spin coating technique was used to deposited the CdS QDs on TiO₂. To obtained the uniform TiO₂/CdS film spin coating was carried out at 1500 rpm for 15 min. Further, CdSe QDs was deposited on TiO₂/CdS film in similar manner by using the fine dispersion of CdSe QDs in hexane. Every layer of deposited QDs on FTO/TiO₂ electrode, it was heated at 75 °C for 20 min for the better film formation. The prepared TiO₂/CdS/CdSe photoanode was annealed at 150 °C

for removing the solvent because it reduces the photovoltaic performance and it was kept at room temperature under dark chamber. Further it uses for fabricating the QDSSCs devices.

2.8.2 Preparation of Counter Electrode

The thin film of the Pt deposited on FTO glass sheet under same active area (0.20 cm^2) was used as a counter electrode by using the doctor blade method and further it was heated at $80 \text{ }^\circ\text{C}$ for 30 min. And, it was annealed at $450 \text{ }^\circ\text{C}$ for 30 min and was cooled at room temperature resulting obtained the homogeneous crystalline thin film of Pt on active area (0.2 cm^2). For fabricating the QD sensitized device, an optimum amount of prepared polymer gel electrolyte was spread on photoanode under the active area and sandwiched both electrode to each other. To prohibited the gel electrolyte penetration in to photoanode and for better contact between electrode and electrolyte, a 0.25 mm thick non-conducting spacer (solar-nix meltonix 1170-25) was used.

2.8.3 Solar Cell Measurement

The current voltage characteristics measurement was estimated by using the multichannel Auto-lab M204 potentiostat / galvanostat combined with Auto-lab Led Driver connected through an optical bench. There are three important parameters such as open circuit voltage (V_{oc}), short circuit current density (J_{sc}) and fill factor (FF) were used to characterize the performance of the fabricated QDSSCs devices and these parameters are directly affected the photovoltaic conversion efficiency (η) of the devices.

2.8. Characterization Techniques:

Different characterization methods were used to characterize synthesized polyurethanes, functionalized polyurethanes, f-MWCNTs, CdS, CdSe and CuInS₂ quantum dots.

2.8.1. ¹H NMR Spectroscopy

Nuclear magnetic resonance spectroscopy was used to estimate the chemical structure of polymer (polyurethane) and its functionalized matrix. ¹H NMR spectroscopy was used to compute the chemical shift and signal intensity corresponding proton with different environment attached with the polymer matrix. Different chemical environment influences the peak position and peak intensity. This approach is also subjected to measure the degree of functionalization on a particular unit of polymer (polyurethane) framework. ¹H NMR spectra was recorded on a Bruker 500MHz spectrometer after dissolving the sample in d₆-DMSO solvent. The homogeneous sample was placed in the magnetic field before spectral measurement. The chemical shifts were recorded in ppm unit relative to the reference sample tetramethylsilane (TMS).

2.8.2. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is an indomitable spectroscopic technique for characterization of organic molecule and polymer or functionalized polymer matrix based on chemical moieties or functional groups present on molecule or polymer chain. The infrared region is from 700 nm to 1000 nm wavelength of light were used to analyzed samples. The absorption of the light by molecules are depends upon the nature of molecule bonded to one another. The sharp (intense) signals were used to measure the position or shifting of peaks. The spectra were recorded in transmission mode by irradiating the solid sample directly. The approach offers high signal to noise ratio for different groups in polymer

framework. Thermo-Nicolet 5700-FTIR was used to record the infrared spectra of solid polyurethane and functionalized (sulfonated) polyurethane in the range of 400-4000 cm^{-1} in ATR mode with the 4 cm^{-1} resolution.

2.8.3. UV-visible Absorption Spectroscopy

UV-visible spectrophotometer is a potent technique to characterize the sample both in liquid phase as well as solid thin film. The technique is used to record spectrogram corresponding to broad peaks of different chromophores linked at polyurethane or sulfonated polyurethane. UV-visible spectrum is distinguished by electronic transition associated with $\pi-\pi^*$ or $n-\pi^*$ transition corresponds to particular functional group or unsaturated groups present in molecule or polymer matrix. The JASCO V-650 UV-vis spectrophotometer was used to analyze absorption spectral behavior of materials in solid state with the spectral range of 200-800 nm wavelengths of the light.

2.8.4. X-ray Diffraction (XRD)

X-ray diffraction pattern of synthesized pure and functionalized polyurethane samples was estimated by using Rigaku wide angle X-ray diffractometer combined with a graphite monochromator using a $\text{Cu K}\alpha$ source with a wavelength $\lambda = 1.54 \text{ \AA}$, and at 45 KV voltage and 200 mA current was used to operate the generator, during all the measurements of sample voltage and current kept constant. The thin film as prepared sample was scanned at diffraction angle (2θ) from 5 to 70° with scan rate 3° min^{-1} .

2.8.5. Dynamic Light Scattering (DLS)

The dimension of the as-prepared quantum dots was determined through dynamic light scattering (DLS). The particle sized in solution phase was calculated by using the Horiba Scientific Nanoparticle analyzer SZ-100 with scanning angle of 90^0 at room temperature.

2.8.6. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (*Supra 40, Zeiss FESEM*) was used to analyzed the surface morphology such as shape, size and volume of the prepared samples. The focused beam with energy range 1 to 50 keV was used for the scanning of the surface of the sample and formation sample image. The lanthanum hexaboride (LaB_6) filament was used to generates the electron beam and these electrons interact with the atoms present in the sample which gives the information about composition and surface morphology of the sample.

2.8.7. Transmission Electron Microscopy (TEM)

The particle size dimension of prepared samples was measured by using the Transmission electron microscope (FEI Technai 20 TEM). TEM instruments voltage range is 80-200 kV and the operating voltage are 200 kV. The ultra-fine dispersed sample was prepared by dissolving the as-prepared QDs in hexane through prob sonication technique and carbon coated copper grid (200mesh) was used as a sample holder. The ImageJ software was used to determine the particle size.

2.8.8. Cyclic Voltammetry (CV)

Cyclic voltammetry is an electrochemical measurements technique was used for the analysis of the synthesized polymer and its subsequent to analyzed the electrochemical behavior (redox

activity). Cyclic voltammetry assessment was conducted to measure its redox potential (oxidation and reduction potential). It is equipped with Pt disc (2 mm diameter) electrode as a working electrode, Pt wire (1 mm diameter) as counter electrode and Ag/AgCl a reference electrode saturated with 3M KCl solution studied at room temperature for acquiring CV profile of diluted solution of different sample in the potential range of -2.0 eV to +2.0 eV of N-methyl pyrrolidone. The cyclic voltammogram was obtained by NOVA 2.1 software at room temperature with scan rate of 20 mV/s.

2.8.9. Linear Sweep Voltammetry (LSV)

LSV is executed to investigate the electrochemical stability window in solution phase of sample with CV assembly at room temperature with a fixed scan rate.

2.8.10. Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy technique is an important tool to investigate the charge transfer resistance of solution based on frequency response analysis. The EIS were recorded between the frequency range of 0.1 Hz to 1 MHz. EIS analysis was broadly used to investigate the intrinsic interfacial charge transfer and to find out the information about electrochemical transport kinetics and photo-electrochemical reaction occurs at the electrode electrolyte interface. The electron transport, recombination and lifetime were analyzed through spectrogram both for materials in solution phase as well as photonically irradiated device.

2.8.11. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis is thermal technique used to analyse the thermal stability of the synthesized polyurethane or functionalized polyurethane. The method represents changes in samples weight as a function of temperature, in a specific atmosphere (N₂ gas). The weight variations are due to presence of specific functionalities or volatile part present in materials. 6 mg of sample was employed on crucible and examined at the rate of 20° min⁻¹ in the temperature range of 40-600°C. The degradation temperature corresponding to 5% weight loss was taken as standard confident limit. TGA analysis was performed on thermo gravimetric analyzer *Mettler-Toledo*. The material was characterized with a thermal degradation curve at particular temperature.

2.8.12. Differential Scanning Calorimetry (DSC)

The differential scanning calorimetry is a most commonly known thermal technique is used to examine thermal behavior of materials. The melting temperature, glass transition temperature and gel transition temperature were scrutinized by *Mettler 832* differential scanning calorimetry. The melting temperature and enthalpy of fusion were evaluated from the plots obtained using area under the curve. The assessment was conducted from room temperature to 300° C at scan rate of 10° C/min. The bidirectional (heating and cooling) cycle was carried out to analyze the gel transition temperature for the same sample with same scan rate.

2.9. Measurements and Calculations

2.9.1. Degree of Sulfonation on Hard Segment Content in Polyurethane Ionomer

Degree of sulfonation (DS) is directly related to the of weight ratio of the sulfonating agent and urethane linkage of polyurethane polymer. It was noted that, the degree of sulfonation are increases

with increasing the sulfonating agent concentration. The degree of sulfonation was measured through following expression

$$DS(\%) = \frac{b/2}{a+b/2} \times 100 \quad (2.2)$$

where, a is the peak intensity or area of the signal corresponding to the hydrogen atoms of -NH group of polyurethane hard segment content and b is the peak height or area of the signal corresponding to hydrogen atoms of -CH₂ groups of sulfonate group attached with polyurethane chains.

2.9.2. Calculation of % Crystallinity

$$\text{Crystallinity (\%)} = \frac{\Delta H_{\text{ionomer}}}{\Delta H_{\text{PU}}} \times 100 \quad (2.3)$$

2.9.3. Calculation of Optical Band Gap and HOMO-LUMO Energy Levels

The size quantization effect or optical band-gap (E_g) of the QDs and polyurethane /sulfonated polyurethane were evaluated by using the relation:

$$E_g = \frac{1240}{\lambda(nm)} \quad \text{and} \quad (\alpha hv)^2 = \beta(hv - E_g) \quad (2.4)$$

where, E_g is the band gap of the material, β is a constant, h is the Planck's constant, α is the absorption coefficient (cm^{-1}), and v is the photon frequency. The Tauc's plots are plots between

$(\alpha h\nu)^2$ versus photon energy ($h\nu$) for prepared various samples. E_g values were determined by the extrapolating of the linear portion of the curve to x-axis at a $\alpha = 0$.

2.9.4. Calculation of HOMO-LUMO Energy Levels

Cyclic voltammogram was used to measured highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels. The oxidation and reduction potentials were recorded by extrapolating onset peak potential at X-axis y = 0.

$$E_{\text{LUMO}} - E_{\text{HOMO}} = \text{Electrochemical energy gap (eV)} = \text{optical band gap (eV)}$$

$$E_{\text{HOMO}} = -eV(E_{\text{ox}} + 4.4) \quad (2.5)$$

$$E_{\text{LUMO}} = -eV(E_{\text{red}} + 4.4) \quad (2.6)$$

2.9.5. Ionic Conductivity

Electrical (ionic) conductivity was analyzed through interfacial charge transfer resistance obtained from Nyquist plot with NOVA 2.1 software. The Nyquist plot is spectrogram which is obtained as a function of real impedance Z' (ohm) vs. imaginary $-Z''$ (ohm). The ionic conductivity was calculated by following relation.

$$\sigma (S/cm) = \frac{l}{R_{ct} A} \quad (2.7)$$

$$\sigma = \sigma_0 \exp -\frac{E_a}{RT} \quad (2.7.1)$$

where l is film thickness or distance between working electrode and counter electrode, R_{ct} (Ω) charge transfer resistance and $A(\text{cm}^2)$ is area of Pt disc (working electrode).

2.9.6. Electronic Conductivity

$$\sigma_{\text{electronic}} = \frac{0.693}{\pi\delta} \frac{\delta I}{\delta V} \quad (2.8)$$

where δ (mm) indicates thickness of the film and $\frac{\delta I}{\delta V}$ slope of the linear fit. Current –voltage characteristic measurements were evaluated for thin film in the potential range -10 V to +10 V.

2.9.7 Electrolyte Uptake or Solvent Absorbent Power

Elevation in liquid electrolyte loading has an acceleration effect on photovoltaic performances.

$$\text{Electrolyte uptake or solvent loading}(\%) = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100 \quad (2.9)$$

2.9.8. Free Electron Lifetime Measurement

Bode plot is recorded as a function of frequency (log f) vs. impedance Z (Ω) in EIS measurement.

The lifetime of free electron or photoexcited electron was calculated through following relation:

$$\tau = \frac{1}{2\pi f_{\text{max}}} \quad (2.10)$$

where τ denotes lifetime of free electrons and where, f_{max} is the frequency at the maximum of the curve in the lower or intermediate frequency region in Bode plot.

2.9.9. Calculation of Peak-to-Peak Separation Potential (E_{PP})

$$E_{PP} = E_{AE} - E_{CE} \quad (2.11)$$

where E_{PP} , E_{AE} and E_{CE} indicate peak to peak separation potential, onset anodic potential and onset cathodic potential, respectively.

2.9.10. Theoretical Calculation of Open Circuit Potential

$$V_{OC} = |E_{CB} - E_{redox}| \quad (2.12)$$

2.10. J-V Characteristic Measurement and its Photovoltaic Parameters

J-V characteristic measurement was analyzed with Metrohm Auto lab, the data was recorded with NOVA 2.1 software. The device was irradiated with He lamp with white light as a neutral source at intensity of 100 mW/cm^2 . The working of a solar cell solely depends upon its semiconductor photovoltaic effect hence a solar cell also known as photovoltaic cell. A solar cell is most commonly known as a semiconductor device. The photo illumination generates photocurrent through photoexcited charge transport and reversible charge transport was sustained through interfacial redox activity of gel polymer electrolyte. The electro catalytic activity was managed

through Pt counter electrode. The photo voltage (V_{OC}) and short circuit current density (J_{SC}) were computed through photogram or photovoltaic curve.

2.10.1. Short Circuit Current Density (J_{sc})

The short circuit current is the current flows through the external circuit when the voltage is zero across the solar cells. The photon flux intensity is directly affected the short-circuit current of a photovoltaic device. The AM 1.5 spectrum was used for the standard measurement of the photovoltaic performance of the fabricated QDSSCs. The short circuit current density (I_{sc}) depends on the area of the solar cell, the spectrum of the solar cells, number of photons, the minority carrier collection probability and optical properties.

2.10.2. Open Circuit Voltage (V_{oc})

The open-circuit voltage is the maximum voltage at which current flows through-out the external circuit is zero, which corresponds to the forward bias voltage. V_{oc} depends on the photo-generated current density. The measurement of the recombination in the photovoltaic devices is known as open circuit voltage (V_{oc}).

2.10.3. Fill Factor (FF)

The fill factor is a ratio of the maximum power ($P_{max} = J_{max} \times V_{max}$) output by a solar cell devices and the product of V_{OC} with J_{SC}

$$FF = \frac{J_{max} \times V_{max}}{J_{sc} \times V_{oc}} \quad \text{or} \quad \frac{P_{max}}{J_{sc} \times V_{oc}} \quad (2.13)$$

where, P_{max} is the maximum power generated by the QDSSCs devices.

2.10.4. Photovoltaic Conversion Efficiency (η)

The power conversion efficiency is a measurement as the ratio of the maximum power generated by a QDSSCs and the power input in the QDSSCs devices. As mentioned above, solar cells are measured under the STC, where the incident light is described by the AM1.5 spectrum and has an irradiance of $P_{in} = 100\text{mW}/\text{cm}^2$

$$\eta (\%) = \frac{P_{\max}}{P_{in}} \times 100 \quad \text{or} \quad \frac{J_{sc} \times V_{oc} \times FF}{P_{in}} \times 100 \quad (2.14)$$