Chapter 5
Sb$_2$S$_3$: Synthesis, Characterization and Its Application as a Sensitizer In Semiconductor Sensitized Solar Cells

This Chapter describes methods and techniques applied for synthesis of Sb$_2$S$_3$ nanoparticles, sensitization of previously prepared porous photoanode of SnO$_2$ with Sb$_2$S$_3$ and cell fabrication. The first part deals with introduction, synthesis of Sb$_2$S$_3$ and supporting experiments for device fabrication. The second part of the chapter describes the techniques used for characterization of the synthesized materials. The third part describes results obtained and discussion over effect of sensitization time on properties of Sb$_2$S$_3$ and Sb$_2$S$_3$ sensitized porous SnO$_2$ photoanodes and their performance in SSSC.
# Sb$_2$S$_3$: Synthesis, Characterization and Its Application as a Sensitizer In Semiconductor Sensitized Solar Cells

## Index

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Chapter 5</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter 5: Sb$_2$S$_3$: Synthesis, Characterization and Its Application as a sensitizer In Semiconductor Sensitized Solar Cells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>112</td>
</tr>
<tr>
<td>5.2</td>
<td>Experimental details</td>
<td>113</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Materials</td>
<td>113</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Substrate cleaning</td>
<td>113</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Deposition of Sb$_2$S$_3$ films</td>
<td>113</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Preparation of porous SnO$_2$ photoanode</td>
<td>115</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Chemical bath deposition of Sb$_2$S$_3$ on the SnO$_2$ photoelectrode</td>
<td>115</td>
</tr>
<tr>
<td>5.2.6</td>
<td>Preparation of electrolyte and counter electrode</td>
<td>115</td>
</tr>
<tr>
<td>5.2.7</td>
<td>Fabrication of solar cell</td>
<td>115</td>
</tr>
<tr>
<td>5.3</td>
<td>Characterizations</td>
<td>115</td>
</tr>
<tr>
<td>5.4</td>
<td>Results and discussion</td>
<td>116</td>
</tr>
<tr>
<td>5.3.1</td>
<td>The phase identification and structural analysis of Sb$_2$S$_3$ films</td>
<td>116</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Structural analysis of Sb$_2$S$_3$ sensitized SnO$_2$ photoanodes</td>
<td>119</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Optical properties of Sb$_2$S$_3$ films</td>
<td>119</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Photoluminescence (PL) analysis of Sb$_2$S$_3$ films</td>
<td>120</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Optical Absorption Spectra of SnO$_2$ film and SnO$_2$/Sb$_2$S$_3$ photoanodes: effect of sensitization time</td>
<td>122</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Surface morphological, Elemental analysis and Contact angle measurement of Sb$_2$S$_3$ films</td>
<td>113</td>
</tr>
<tr>
<td>5.3.7</td>
<td>Surface morphological, elemental analysis and contact angle measurement of Sb$_2$S$_3$ sensitized SnO$_2$ photoanodes</td>
<td>125</td>
</tr>
<tr>
<td>5.4</td>
<td>Photovoltaic characterization of solar cell based on Sb$_2$S$_3$ sensitized SnO$_2$ photoanode</td>
<td>128</td>
</tr>
<tr>
<td>5.5</td>
<td>Conclusion</td>
<td>130</td>
</tr>
<tr>
<td><strong>Reference</strong></td>
<td></td>
<td>132</td>
</tr>
</tbody>
</table>
5.1 Introduction

Nanostructured semiconductors have been attracting great attention over past few years because of their novel electrical and optical properties which originated due to quantum confinement effect [1-4]. These size dependent optical properties have many potential applications in the areas of solar energy conversion, light emitting devices, chemical or biological sensors and photocatalysis [5-9]. Of the many available semiconductors, metal chalcogenides in the nano regime have assumed great importance by virtue of their applications in optoelectronic devices including photovoltaics. This is due to their tunable optical and structural properties. Among chalcogenides, antimony trisulfide (Sb$_2$S$_3$), a group V-VI semiconducting material, is a promising candidate as a target material in television cameras [10], microwave devices [11], switching devices [12], and various optoelectronic devices [13, 14]. With its optical band gap between 1.7-2.3 eV, Sb$_2$S$_3$ in its nano form is capable of absorbing most of the visible spectrum of the solar radiation [15-17]. Therefore, it has of late emerged as a potential candidate in solar cell applications.

Photoluminescence (PL) is one of the important photophysical properties which is used to characterize semiconductors with special reference to metal chalcogenides, to ascertain their suitability in various optoelectronic applications. As stated above, the optical absorption of Sb$_2$S$_3$ makes it one of the suitable candidates in photovoltaic applications. However, the quality of these nanomaterials for their optoelectronic applications is better evaluated when their photoluminescence properties are studied. The optical properties like optical absorption and PL of nano materials do also depend on the method of their synthesis. Though there are many reports available on the luminescence studies of group V-VI semiconductors in the literature [18]. There are only countable communications on Sb$_2$S$_3$ with reference to its photoluminescence property [19-21]. Though, there are numerous reports on the synthesis of nanocrystalline Sb$_2$S$_3$ [22-24] and chemical bath deposition is one of the most simple and facile way of preparing the nanocrystals of this material. In spite of existence of umpteen reports on Sb$_2$S$_3$ synthesized using CBD, to the best of our knowledge, there are no reports available...
which deal with the photoluminescence studies on Sb$_2$S$_3$ prepared from chemical solution deposition [25-27].

In the present work, Sb$_2$S$_3$ nanocrystals are synthesized using chemical solution deposition and an attempt has been made to explain the evolution of their morphology. The photoluminescence studies of the prepared nanocrystals are conducted and the probable reasons for the resultant spectra are explained.

**5.2 Experimental**

**5.2.1 Materials**

All chemicals (Antimony chloride (SbCl$_3$) (Merck), Sodium thiosulphate (Na$_2$S$_2$O$_3$) (SRL), Ethylene diamine tetraacetic acid (EDTA) (SRL) were of the highest purity available and they were used without further purification.

**5.2.2 Substrate cleaning**

To deposit Sb$_2$S$_3$ films and to prepare SnO$_2$ photoanodes the glass substrates and FTO were cleaned using procedure discussed in section 2.2 of chapter-3.

**5.2.3 Deposition of Sb$_2$S$_3$ films**

In the present synthesis, solutions of antimony chloride (SbCl$_3$) and sodium thiosulphate (Na$_2$S$_2$O$_3$) were prepared in acetone and double distilled water respectively in two different beakers, wherein SbCl$_3$ acts as a precursor of Sb$^{3+}$ and Na$_2$S$_2$O$_3$, that of S$^{2-}$ as explained in the following steps. First, the bath for Sb$^{3+}$ was prepared by adding 1.5 gm of SbCl$_3$ to 15 ml of acetone and stirred for 10 minute until a uniform mixture was formed. Second, 5 ml of Ethylene diamine tetraacetic acid (EDTA) (1M), a complexing agent was then prepared in double distilled water by dropping 2-3 pellets of NaOH through vigorous stirring and added to the first bath containing antimony source to obtain Sb$^{3+}$-EDTA complex. Third, a 2M S$^{2-}$ precursor solution was prepared in double distilled water under constant stirring of 10 minute. Fourth, S$^{2-}$ precursor solution was slowly introduced into the Sb$^{3+}$-EDTA complex precursor solution under constant stirring. EDTA helps for obtaining soluble species of Sb$^{3+}$ in acidic medium during the
reaction. The color of the mixture solution was observed to be changing from milky white to lemon yellow, dark yellow and then to orange indicating the formation of Sb$_2$S$_3$ species. The synthesis process is considered to be based on slow release of Sb$^{3+}$ and S$^{2-}$ ions in bath. The reaction was carried out at different temperatures, viz. room temperature (RT), 60 and 80°C and each sample was taken out after completing the desired reaction time of 30, 60 and 120 m, respectively for each temperature. The samples deposited at room temperature were named as A, B and C, in the increasing order of reaction time of 30, 60 and 120 m, respectively. In the same manner, rest of the samples were named as D, E, F, G, H and I, which were deposited at 60 and 80°C, for reaction times of 30, 60 and 120 m, respectively. Figure 5.1 shows the step-wise reaction process for the deposition for the deposition of Sb$_2$S$_3$.

![Flow chart of the reaction process for deposition of the Sb$_2$S$_3$ films.](image)

**Figure 5.1** Flow chart of the reaction process for deposition of the Sb$_2$S$_3$ films.
5.2.4 Preparation of porous SnO\(_2\) photoanode

The photoanode is prepared by using method as discussed in section 3.4 of Chapter 3. The resultant films were named as bare or un-sensitized SnO\(_2\) photoelectrodes.

5.2.5 Chemical bath deposition of Sb\(_2\)S\(_3\) on the SnO\(_2\) photoelectrode

The previously prepared SnO\(_2\) photoelectrodes were introduced vertically into the bath containing both Sb\(^{3+}\) and S\(^{2-}\), at room temperature for the deposition of Sb\(_2\)S\(_3\) over the porous nanocrystalline SnO\(_2\). After carrying out sensitization for different time durations of about 30, 60 and 120 minutes, the photoelectrodes were withdrawn from the bath and the corresponding photoanodes were named as PC-30, PC-60 and PC-120, respectively. The sensitized photoelectrodes were observed to be coated with increased darkening of brownish tinge of the photoanodes from PC-30 to PC-120. This may be due to the enhanced level of deposition of nanocrystalline Sb\(_2\)S\(_3\) onto the bare photoanodes of SnO\(_2\) with increase in sensitization time.

5.2.6 Preparation of electrolyte and counter electrode

a) Electrolyte: As discussed earlier in section 3.2.6 of Chapter 3.

b) Counter electrode: As discussed earlier in section 3.2.6 of Chapter 3.

5.2.7 Fabrication of solar cell

The Sb\(_2\)S\(_3\) sensitized SnO\(_2\) photoelectrode and counter electrode were clamped together into a sandwich type configuration with droplet of polysulphide electrolyte injected between them. The fabricated solar cells using photoelectrodes PC-30, PC-60 and PC-120 were named CC-30, CC-60 and CC-120, respectively and characterized to study their photovoltaic performance.

5.3 Characterizations

The prepared films of Sb\(_2\)S\(_3\) films, un-sensitized SnO\(_2\) photoanode and Sb\(_2\)S\(_3\) sensitized SnO\(_2\) photoelectrode films were characterized for crystal structural analysis, optical
properties, morphological analysis, elementary analysis and photovoltaic performance using the techniques described in section 3.3 of chapter 3. The emission spectrum for all samples was recorded by using photoluminescence spectroscopic technique (Perkin Elmex LS55, He-Ne LASER line (325 nm) as excitation source) at room temperature.

5.4 Results and discussion

5.4.1 The phase identification and structural analysis of Sb$_2$S$_3$ films

Figure 5.2 shows XRD patterns for samples A-I. It can be seen from Figure 5.2 (a) that diffractograms for samples A and B have a defined peak around $2\theta = 45.75^\circ$ which has apparently preferred orientation along (440) direction. It is also observed that, the sample C turned polycrystalline. However, Figure 1 shows that from samples D-F, the polycrystallinity enhanced with both, deposition time and temperature. Interestingly, at deposition temperature of 80°C, all the samples showed polycrystallinity. All defined peaks were matched with (JCPDSFile No: 42-1393), confirming the orthorhombic phase for deposited Sb$_2$S$_3$ in all samples namely A to I.

This may be explained invoking the regular growth kinetics of formation of nanocrystals in chemical bath deposition as a function of deposition time and temperature. It appears that in samples A-C, the nucleation and growth of nanocrystals is purely driven by the increase of deposition time. The mechanism of crystal growth in chemical solution deposition is a well understood phenomenon [28]. The ions or molecules in the reaction bath collide with each other and form embryos. The embryos have a critical size beyond which they redissolve into the solution and are thus, thermodynamically unstable. Inheterogeneous nucleation like the present case, the introduction of the solid substrate into the solution facilitates nucleation over the substrate. The energy required for the formation of interface between the embryo and the solid substrate is low vis-a-vis the energy required for the homogeneous nucleation in the solution. At low temperatures or near room temperature, the cationic and anionic species in the solution to be deposited get adsorbed over the embryo or nuclei and start growing into a crystal. In general, in chemical bath deposition where thermal treatment is not involved, the crystals start growing along the geometric orientations which minimize the
energy configuration of the system. In the present report, the Sb\(_2\)S\(_3\) nanocrystals in samples A and B have a preferred orientation along [440] at room temperature probably, due to the above said reasons. This is also in agreement with the fastest model in the literature [29] which states that the nucleation with various orientations can be formed at the starting of the deposition and the nuclei compete with each other to grow. The nuclei having the fastest growth rate survives resulting in preferred orientation as obtained in samples A and B. The probable mechanism of formation of the observed crystalline phases for samples A to B is illustrated in the schematic as shown in the Figure 5.2 (b). However, with increase of deposition time, the growth of nucleations in other orientations gains momentum resulting in crystals with random orientations, leading to the polycrystallinity of sample C [29].

However, from samples D-F, in addition to deposition time deposition temperature also apparently contributed to the increase in reaction rate. At a temperature greater than room temperature, the random motion of the Sb\(^{3+}\) and S\(^{2-}\) ions due to the acquired thermal energy might have forced the nuclei to grow in different crystal orientations giving rise to polycrystallinity in the deposited Sb\(_2\)S\(_3\) films (See Figure 5.2-a (D-F)). But, for the subsequent samples viz. G-I, the deposition temperature seems to have dominated the growth kinetics over the deposition time. As a result of this, all the samples namely G to I, turned polycrystalline irrespective of deposition time (See Figure 5.2-a (G-I)). It is also observed that with increase of temperature a characteristic peak of Sb\(_2\)O\(_3\) has appeared. This may probably be attributed to oxide formation of antimony at temperatures 60 and 80° C, respectively. The peak around 2\(\theta\) = 26.66° matched with (JCPDSFile No: 74-1725), marked with “*” in XRD patterns stands for Sb\(_2\)O\(_3\).
Figure 5.2 (a) XRD patterns of Sb$_2$S$_3$ samples A-I

Figure 5.2 (b) The schematic showing probable mechanism of formation of the observed crystalline phases for samples A, B and C.
5.4.2 Structural analysis of Sb$_2$S$_3$ sensitized SnO$_2$ photoanodes

Figure 5.3 shows diffraction pattern for unsensitized SnO$_2$ photoelectrode with defined peaks at $2\theta = 26.63$, $34.07$, $38.20$, $52.18$ and $55.19$° corresponding to the diffraction from add planes which confirm its tetragonal phase (JCPDS file no: 41-1445). Figure 5.3 also shows the diffraction patterns related to PC-30, PC-60 and PC-120, respectively. PC-30, PC-60 and PC-120 show diffraction signatures corresponding to both, Sb$_2$S$_3$ and SnO$_2$. In PC-30, PC-60 and PC-120, Sb$_2$S$_3$ nanocrystals appeared in the orthorhombic phase (JCPDSFile No: 42-1393).

5.4.3 Optical absorption study of Sb$_2$S$_3$ films

The UV-vis wavelength dependent absorption spectra recorded for samples A-I are shown in Figure 5.4 (a-c). The absorption edges of the spectra show an apparently clear red shift with respect to that of bulk from samples A to C, D to F and G to I. This corroborates with the enhancement in the crystallinity of nanoparticles with increase of deposition time as well as bath temperature, as discussed in the results of X-ray Diffractometry and SEM.

![Figure 5.3 XRD patterns for unsensitized SnO$_2$ photoanode, PC-30, PC-60 and PC-120.](image-url)
Inset of Figure 5.4 (a-c) shows the band gap calculations made from the absorbance spectra. The optical band gap values for samples A-I were found to be in the range 1.9 to 2.0 eV. Such a variation is in agreement with the literature reports [30]. The observed blue shift in optical band gap of samples from I-A with respect to bulk may be attributed to quantum confinement effect. Good optical absorption in the visible region by the Sb$_2$S$_3$ nanocrystalline films prepared from the chemical solution deposition suggests that, this material is suitable for photovoltaic applications. The same was confirmed by different research groups [31, 32].

5.4.4 Photoluminescence (PL) analysis of Sb$_2$S$_3$ films

Figure 5.5 (a) shows the photoluminescence spectra of Sb$_2$S$_3$ films A-I. It is observed from PL spectra for films A-I that the emission spectra are identical in shape but, the bands differ only in intensities. PL spectra for all samples exhibit two distinct emission peaks at around 610 nm (2.03 eV) and 717 nm (1.72 eV), respectively.

The peak centered at around 610 nm may be attributed to the band edge luminescence of Sb$_2$S$_3$ nanocrystals and is in agreement with the obtained optical band gap in the range of 1.9-2 eV as discussed before in the results of optical absorption spectroscopy.

Such a phenomenon of band edge luminescence is well known and widely reported in the literature for semiconductor nanocrystals [33, 34]. However, in the present study, it is observed that, the PL intensity of this peak decreased with increase of bath temperature of the samples, which may be attributed to increased defects introduced in the nano system due to the enhanced thermal energy of the bath [33].

The PL spectra also show striking emission peak in the visible range at around 717 nm for all the samples. However, it is observed that, the intensity of the peaks varied with both, reaction time as well as bath temperature [35]. Appearance of such PL signatures may be attributed to the presence of sulphur vacancies.
Figure 5.4.1 Wavelength dependent absorption spectra of samples (a) A to C (b) D to F and (c) G to I; Inset shows Bandgap calculation from absorption spectra of corresponding samples.

There are reports available in the literature supporting such attributions [33]. Interestingly, conspicuous increase in the broadening of the PL spectra was observed for samples A-I, which may be attributed to the increased size distribution of Sb$_2$S$_3$ nanocrystals formed with increase of both deposition time and bath temperature. It may also be observed that, the position of the stoke shifted emission peak for all the samples is apparently the same irrespective of the intensities, allowing us to infer that the probable origin of such a feature in all the samples is the same and may be due to the presence of sulphur vacancies as discussed above. The probable emission transitions are shown in the schematic of Figure 5.5 (b). In view of the above, Sb$_2$S$_3$ with its luminescence properties, is suitable for optoelectronic applications.
Figure 5.5 (a) PL spectra recorded at room temperature of Sb$_2$S$_3$ films deposited at three different bath temperatures and reaction times (b) The schematic showing probable emission transitions for Sb$_2$S$_3$ films.

5.4.5 Optical Absorption Spectra of SnO$_2$ film and SnO$_2$/Sb$_2$S$_3$ photoanodes: effect of sensitization time

The absorption spectra of the unsensitized SnO$_2$, PC-30, PC-60 and PC-120 are shown in Figure 5.6. It is seen from the Figure that, the absorption for unsensitized SnO$_2$ is limited to the ultraviolet region of electromagnetic spectrum. However, for all sensitized photoelectrodes, the absorbance is enhanced in the visible region. It may be noted that, the intensity of the absorption spectra increases in the visible region from 400 to 600 nm with the increasing sensitization time from PC-30 to PC-120. This fact suggests that amount of loading of a sensitizer increases with increase of loading time resulting in enhanced absorption of visible light from PC-30 to PC-120. Also, there is an apparent red shift in the absorption feature from PC-30 to PC-120, which is probably a consequence of increase in particle size of sensitizer with increase of deposition time and may be attributed to the aggregation of sensitizer on the surface of bare photoelectrode.
Figure 5.6 Optical absorption spectra for unsensitized SnO2, PC-30, PC-60 and PC-120.

5.4.6 Surface morphological, Elemental analysis and Contact angle measurement of Sb₂S₃ films

In the present study, both bath temperature and reaction time were found to be playing an important role in deciding reaction rate during the chemical bath deposition of Sb₂S₃, giving rise to evolution of different morphologies. Figure 5.7 shows the temporal and temperature dependent evolution of morphology for samples A-I. Figure 5.7 (A-C) shows micrographs of samples A-C. It may be observed that, for the same magnification there is a change in morphology of the crystalline Sb₂S₃ from grainy aggregates to dispersed nanoparticles from sample A to B. with further increase of reaction time up to 120 m, the nanospheres of diameter of about 80-100 nm have formedas shown in Figure 5.7 (C). However, the size of the nanoparticles in Figure 5.7 (E) and 5.7 (F) is observed to be greater than that of Figure 5.7 (B) and 5.7 (C), respectively. Such a difference in particle size may be attributed to the increase in bath temperature in the former vis-à-vis the latter. As discussed before, the particle size is a function of deposition temperature in chemically deposited films. Figure 5.7 G-I show flake-like grains graduating to form large spherical grains probably due to the combined effect of both bath temperature and
reaction time. Also, for the same deposition time of 120 m, all samples Viz. C, F and I showed enhanced crystallinity for different bath temperatures. This is in agreement with the X-ray diffractograms of the same samples. Transpiration of spherical morphology of Sb$_2$S$_3$ nanoparticles observed in the present study is in support of report in the literature [36].

![Figure 5.7](image)

**Figure 5.7** Scanning electron micrographs of samples A, B and C.

Compositional and elemental analysis of Sb$_2$S$_3$ films by EDAX spectrum is shown in Figure 5.8. It reveals the presence of Sb and S confirming the formation of Sb$_2$S$_3$.

Figure 5.9 shows the contact angle measurement for Sb$_2$S$_3$ films. It can be seen from the Figure 5.9 that contact angle decreases with increase in deposition time, coincides with the increase in crystallinity of films. The acute angle of contact reveals the hydrophilic nature of the deposited films of Sb$_2$S$_3$. 
Figure 5.9 Schematic representing contact angle measurement for samples A, B and C.

5.4.7 Surface morphological, elemental analysis and contact angle measurement of Sb₂S₃ sensitized SnO₂ photoanodes

To further analyze the effect of sensitization time on the SnO₂ photoelectrode, morphology of both bare and sensitized photoelectrode was studied. Figure 5.10 shows the scanning electron micrographs for sensitized SnO₂ photoelectrode with different
sensitization times. It is clearly seen from Figure 5.10 that, the pores in SnO$_2$ photoelectrode are filled up with nanocrystalline Sb$_2$S$_3$. The pore-filling apparently increased with increase of deposition time from PC-30 to PC-120. In addition to this, there is no observable alteration in the surface quality and structure of the SnO$_2$ photoelectrodes with the increase in sensitization time.

**Figure 5.10** Scanning electron micrographs of samples P-30, P-60 and P-120.

**Table 5.1** Elemental (% atomic) analysis of bare SnO$_2$ and SnO$_2$ photoanodes sensitized with Sb$_2$S$_3$ for three different sensitization times.

<table>
<thead>
<tr>
<th>Photoanode</th>
<th>Sensitization Time (minute)</th>
<th>Sn</th>
<th>O</th>
<th>Sb</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare SnO$_2$</td>
<td>--</td>
<td>39.97</td>
<td>60.03</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>PC-30</td>
<td>30</td>
<td>24.09</td>
<td>73.34</td>
<td>1.91</td>
<td>0.66</td>
</tr>
<tr>
<td>PC-60</td>
<td>60</td>
<td>23.45</td>
<td>66.11</td>
<td>4.45</td>
<td>5.99</td>
</tr>
<tr>
<td>PC-120</td>
<td>120</td>
<td>21.93</td>
<td>63.56</td>
<td>6.86</td>
<td>7.65</td>
</tr>
</tbody>
</table>

Supplementary elemental analysis by EDAX for un-sensitized and sensitized photoelectrode was carried out and shown in Figure 5.11. EDAX spectrum for un-sensitized film reveals the presence of only Sn and O, that of all sensitized films shows the presence Sb and S in addition to Sn and O. The quantitative analysis obtained by EDAX shows an overall increment in the amount of Sb and S from PC-30 to PC-120,
with increasing deposition time. It is also observed that Sb/S ratio leads to the stochiometric value of 2/3 for sensitization time of 120 m (Table 5.1). Therefore, the XRD results along with EDAX spectrum analysis demonstrate sensitization of SnO$_2$ qualitatively using CBD.

Figure 5.12 shows the contact angle measurement (CAM) for the un-sensitized and Sb$_2$S$_3$ sensitized photoanode. It can be observed from the CAM for unsensitized SnO$_2$ photoanode that, angle of contact for water droplet with its surface is about 42°.

This reveals the hydrophilic nature of photoanode, which may be attributed to the presence of porous network for prepared SnO$_2$ photoanode. Such a porous network is helpful for the loading of semiconductor sensitizer during sensitization in SSSC applications. However, interestingly the hydrophilicity is observed to be increased after sensitization which can be observed from the Figure 5.12. The possible reason for this is as discussed earlier in section 3.4.6 of chapter 3. This increased hydrophilicity may help to enhance the access of electrolyte species during photovoltaic action for extraction of holes.
5.5 Photovoltaic characterization of solar cell based on Sb$_2$S$_3$ sensitized SnO$_2$ photoanode

The photovoltaic performance of solar cells CC-30, CC-60 and CC-120 was investigated by conducting photocurrent density ($J$) versus voltage ($V$) measurements. Figure 5.13 shows the J-V curve for solar cells CC-30 and CC-60. The photovoltaic parameters like short circuit current density ($J_{sc}$), open circuit voltage ($V_{oc}$), fill factor (FF) and photovoltaic efficiency ($\eta$) are obtained from the J-V curves and listed in Table 5.2.

**Table 5.2.** Photovoltaic parameters of Sb$_2$S$_3$ sensitized SnO$_2$ photoanode based solar cell prepared with different sensitization time.

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>Sensitization Time (minute)</th>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
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<tbody>
<tr>
<td>CC-30</td>
<td>30</td>
<td>384</td>
<td>0.803</td>
<td>65</td>
<td>0.66</td>
</tr>
<tr>
<td>CC-60</td>
<td>60</td>
<td>240</td>
<td>0.890</td>
<td>34</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Figure 5.13 Photocurrent versus photovoltage characteristics for solar cells CC-30 and CC-60.

It is observed that, with increase in sensitization time, the value of $J_{sc}$ increases, while $V_{oc}$ shows decrease in its value from CC-30 to CC-60. However, in spite of better optical absorbance of PC-120 that of PC-30 and PC-60, cell fabricated using it does not compensate for photovoltaic performance. This may be due to the over aggregation of sensitizer over the surface of the photoanode.

With increase of sensitization time, the optical absorption spectra as given in Figure 5.6 clearly show an enhanced amount of loading of the sensitizer into the photodelectrodes. This is evident from the improved optical absorption in the visible region. Such an enhanced absorption of light in the visible region leads to generation of increased number density of excitons at the electrode-electrolyte interface. The excitons so generated, get dissociated at the SnO$_2$-Sb$_2$S$_3$ interface due to the favorable interfacial band energetics (see Figure 5.14) leading to effective electron injection from excited Sb$_2$S$_3$ to
the conduction band of SnO$_2$, which further results in improved photocurrent ($J$) in CC-30 and so doubling of $J_{SC}$ in it.

On the other hand, as shown the aggregation of sensitizer molecules delay the transfer of excited electrons from sensitizer to the conduction band of SnO$_2$, giving rise to the recombination of excited electron with the electrolyte present in the porous network of nanostructured SnO$_2$. This lead to the decrease in photovoltage $V$ and thus, Voc for CC-60. Such a mechanism apparently explains the reduction of Voc, for CC-60. Relatively better photovoltaic efficiency of CC-30 vis-a-vis other cells may be obviously attributed to its improved photovoltaic parameters.

![Figure 5.14](image)

**Figure 5.14** Schematic representing relative energy positions of SnO$_2$/Sb$_2$S$_3$ interface.

### 5.6 Conclusions

In summary, the structural and optical properties as a function of reaction time and bath temperature of chemically deposited nanocrystalline Sb$_2$S$_3$ were investigated. The study described the evolution of the crystallinity as well as morphology of the deposited films with good correlation between the two. The crystallinity and the particle
size were observed to have increased with both, reaction time and bath temperature. The optical absorption and luminescence properties of the obtained nanocrystalline films of Sb$_2$S$_3$ revealed that, these nano systems are suitable for optoelectronic applications including photovoltaics.
References


